Justin B. Hollander

The First City on Mars

An Urban Planner's Guide to Settling the Red Planet

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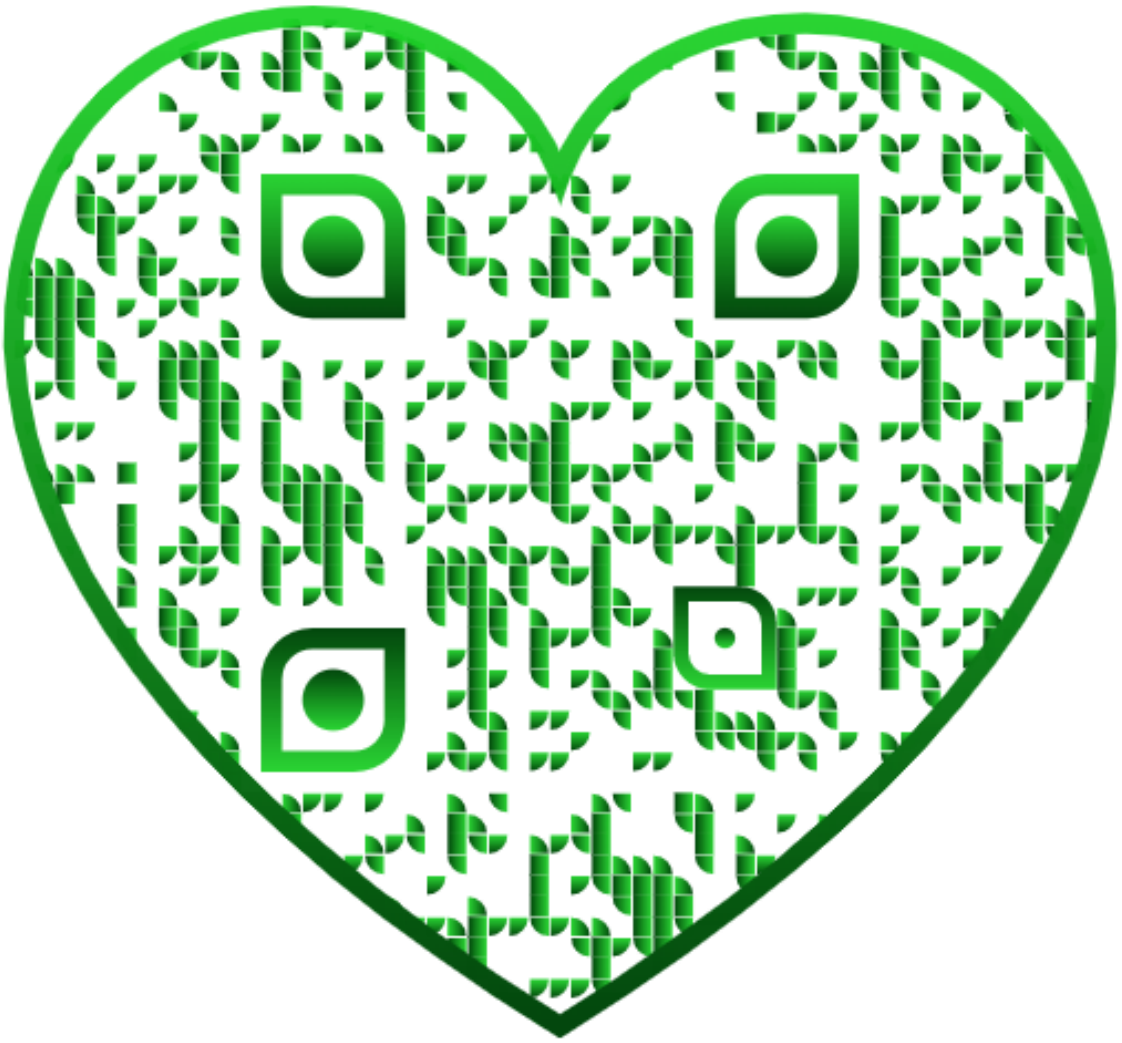

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Foreword

There will be towns and then cities on Earth's Moon and on Mars sooner than you might think. That is inevitable, just like the first settlers on the East Coast of America were destined to move across the entire continent.

It is in our human nature to explore and then pioneer. This leads to transportation systems that enable the establishment of forts and trading posts, then towns, then cities. It's what humans do.

The sooner professionals in a wide range of disciplines focus on the long-term thinking, research, planning and design of cities off-world, the better. The better to make them humane, sustainable, beautiful places where people can be proud and love living there.

These places will then launch bold new adventures, moving further out into our Solar System and then beyond.

This book is perfectly timed and in great need as a highly researched and reasoned foundation by a world-class professional urban planner. It will move the concept of settling Mars forward.

Why and Why Now?

The two richest men in the world, Jeff Bezos and Elon Musk, both started rocket companies and have plans to establish the means and infrastructure for humankind to move out into the Solar System and do it over the next few decades.

And they are not alone. There are several other billionaires, mega-corporations and a growing number of countries starting their own space programs and encouraging private space enterprise.

Financial industry analysts are forecasting the overall worldwide space industry to pass the $1.1 trillion level by 2040. That's only 17 years from now!

Musk started SpaceX for a specific reason: to build a city on Mars for a million people.

> *Entrepreneur **Elon Musk** has claimed he's confident there will be a **city** of 1 million on **Mars** by 2050, transported there by 1000 Starships proposed by his SpaceX venture, with plans for up to three rocket launches per day.*
> *Mirage News*, Mar 19, 2021

People betting against Elon Musk lose. People betting against pioneers with the deep attitude that failure is not an option lose big.

One of the most well-regarded space investment companies is called The Space Fund, based in Texas. They do a significant amount of tracking of how the space enterprise industry is evolving. Their SpaceFund Reality (SFR) is becoming an important industry standard. The SFR rating is designed to provide investors, customers, regulators, media, and the industry itself with a quick guide and assessment of players old and new in the various subsectors of the space industry, including:

- Transportation
- Communication
- Human Factors
- Supply Chain
- Energy

All are vital parts of any serious Mars city planning and design.

Musk and most other people pioneering the space frontier are not urban planners. This is why Justin's book is so important now.

A Preview of the Book

The First City on Mars does something no other book has done: it has laid out a serious scholarly framework to approach urban planning on Mars, drawing on the best science and engineering knowledge and putting it all together in a coherent, logical, human-centered plan for the first city on Mars.

The book begins with a concise history of our spacefaring experience, highlighting the remarkable advances humans have made in just seven decades. The focus of this history is on space architecture and urbanism, with lessons

derived mainly from the two decades of experience we now have colonizing low-Earth orbit aboard the International Space Station (ISS).

Next, the book considers the notion of colonization – warts and all – and draws some insightful conclusions about what city planners on Mars need to know from the experience of colonizers of Asia, North America, and Oceania in the 16th through 20th centuries.

The next four chapters review the psychological, transportation, construction, and other infrastructure dimensions of building cities, reviewing the state-of-the-art science and best practices, focusing particularly on inhospitable, arid, and frigid spots on Earth – close analogs to Mars. Principles for each of these dimensions are presented at the end of each chapter, which are fed into a plan for a Martian city in Chap. 11.

Before launching into that plan, Hollander spends two chapters reviewing precedents, examples of where thoughtful and creative writers, scientists, and explorers put pen to paper and articulated a vision of a city on Mars, and more broadly in outer space.

I am pleased that my plan for a proposed Mars World city of the future experience park and luxury resort for Las Vegas is included in this analysis and particularly happy to see elements from my plan – and many others – included in the final plan Hollander shares in Chap. 11.

The book then concludes by acknowledging the limitation of the approach Hollander took here and points readers to avenues for taking the implications of this book both beyond Mars into the Solar System and right here on Earth.

My Career as a Space Architect

It made good sense when Justin asked me to write the foreword to this book. I'm trained as an architect and for the past 30 plus years have been pioneering outer space architecture, working with NASA and space enterprise companies on the design of the ISS and several other real "human-rated" projects, including Moon bases and Mars mission planning and habitat design.

Human-rated means that people will be living and working in the spaceships or space facilities, so the design and engineering and safety systems must be significantly more robust than for un-manned vehicles. They are also far more expensive and complicated.

Much of my Mars design work has been done with Dr. Buzz Aldrin, famed astronaut from the historic Apollo 11 first Moon landing and a very good designer in his own right. He is full of ideas and passionate about Mars exploration and settlement. He and I advised movie director and producer James

Cameron of *Terminator, Titanic* and *AVATAR* movie fame on a film he is working on about Mars. That was fun.

I only work on human-rated space projects. To date four of them have flown in space, some multiple times. They include the ISS; SpaceHab, a module added to the Space Shuttle cargo bay that doubled the living and working areas; and the Endeavor Space Shuttle Mid Deck.

I was also involved at the beginning of Bob Bigelow's inflatable modules for Bigelow Aerospace orbital hotel and lunar hotel. One of his small modules is attached to the ISS, which the crew uses as a storage area. I'm currently designing a real orbital super yacht called *Destiny* that would be assembled in orbit and provide amazing experiences for 10 passengers and 6 human crew members. Also, I'm doing early planning and design for the first Orbital Yacht Club that would provide the same services as ocean yacht clubs.

For several years I worked with Buzz Aldrin on his concept and designs for Mars Cyclers that would use the gravitational pull and push of the Earth and Mars as a transportation system between the planets. Like sailing ships that use trade winds and ocean currents to move them, the Mars Cyclers would be the carrier vehicle for smaller space ships that would hop on and off as they pass Earth or Mars.

Some of the exciting challenges of planning and designing a real Mars City is that you have to get deep into the sciences and other issues far beyond a city on Earth. You have to deal with traveling at least 50 million miles one way. Mars has 38% of normal Earth gravity and only 44% of the sunlight that reaches Earth. Basically, it has no atmosphere, so you need to create your own air and clean it and move it around.

While Mars has large deposits of ice, you need to mine it and turn it into drinking water and grow your own food. The only building materials are sand and rock. And you must have significant radiation shielding on the way to and on the planet. On top of that, you need to generate your own energy. The best reliable energy sources for space at the moment are small nuclear reactors.

In parallel with my real outer space architecture projects I have been creating, designing, and building space/future themed entertainment projects around the world and consulting on many other space themed movies and TV shows. Working on real space projects adds an authenticity to my space entertainment projects, which in turn promotes real space exploration and settlement.

For the Mars World project, authenticity is critical to this highly immersive invented world, so I spent years planning and designing a real Mars city first, then used it as a model for the Earth-based experience park.

I'm also the senior space science and futurist for the Science and Entertainment Exchange based in Los Angeles, a small division of the U.S. National Academy of Sciences. The Exchange connects movie, TV and game producers, directors, writers, production designers to scientists and other specialists in a wide variety of fields to help make the science in media projects more real and accurate.

I'm also the founder (1996) of the Space Tourism Society (STS), which envisions orbital cruise ships, orbital super yachts and lunar resorts. To have these happen, we need urban planning as noted in this book for Earth orbit and on the Moon. When you add the space sports industry and media industry to the group of activities flooding outer space, you begin to realize we are not far away from needing to start planning these off-world towns, then eventually cities.

Conclusion

If you are reading this book, you are already interested in space exploration and settlement. You may well be in a career making these important things happen. If not, this book is an inspiring guide to getting into such a career and making a real difference.

You can be part of creating a healthy, sustainable, and amazing future for all humankind off-world, and be part of a growing community of like-minded people doing just that right now.

I'm reminded of a quote that has had a strong influence on my life and career:

> *The best way to predict the future is to invent it.*
> Alan Kay, Inventor of the overlapping Window interface for personal computers, *Popular Science*, Summer 2001

If you are new to the space community, here are some groups you can join and get directly involved:

- The National Space Society (NSS). They hold annual space settlement design competitions you can participate in.
- Attend the International Space University (ISU)
- The American Institute of Aeronautics and Astronautics (AIAA)
- Explore Mars Inc. and their annual *Humans to Mars* (H2M) conference
- The Space Tourism Society (STS)

- The annual Space Tourism Conference
- The Space Foundation in Colorado Springs and their annual Space Symposium
- Get a job working for SpaceX or Blue Origin or one of the many current and emerging space enterprise companies around the world.

Enjoy the book. It's a good read and a reference source you can use for years to come.

Outer Space Architect, Founder of the Space Tourism Society (STS)

John Spencer
Los Angeles, California, USA

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About the Author

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1

Welcome to Mars

Between NASA, Elon Musk, Amazon, and the China National Space Administration, there is a veritable space race to Mars. The stuff of science fiction for generations, today there is a broad consensus that somebody is going to land spacecraft and then humans on the Red Planet in the coming decades (Panagiotopoulos 2017; Seedhouse 2009). The dream of visiting Mars may only be eclipsed in human imagination by the exhilarating notion of settling this distant planet. Andy Weir's bestselling novel-turned-Hollywood-hit, *The Martian*, struck audiences as realistic and attainable. The novel's protagonist, Mark Watney, coyly refers to his successful agricultural efforts of growing potatoes in a makeshift indoor farm as the precise definition of colonization. But Weir is not the first human to fantasize about a permanent settlement on Mars. Hundreds of novels, films, and TV shows have speculated about what it would be like for us Earthlings to build cities on Mars (see a distillation of these in Abbot 2016). While the first streets may be decades from being laid out, early planning is well underway at government, nonprofit, and for-profit organizations globally. This multitude of space nerds is working on more than sci-fi; they are preparing for a real, long-term human presence on Mars.

Unfortunately, most know nothing about city planning and design.

That is where I come in. In this book, I lead the reader through centuries of accumulated knowledge about the best, most effective, and most just ways to plan and design cities, and then apply all that insight to perhaps the greatest challenge humans have ever faced: colonizing another planet. It is fun to think of rocket ships that slip out of Earth's atmosphere and travel 50 million miles to another planet, and to perhaps ruminate on those first explorers, the

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early scientists who study Martian soil and seek out water, like Mark Watney in *The Martian*. But here on Earth, it is cities that serve as the "nucleus of civilization", as Thomas Wilson (2016) writes, and the future of life on Mars will require such settlements as well.

What exactly do I mean here by the term "urban planning"? A simple question, right? Renowned urban planning theorist John Friedmann (1996) famously wrote "planners are notorious for the difficulties they have in explaining to others – parents, friends, university administrators – what they do" (p. 94). Best to take a step back from planning and define the bigger concept: public policy. While this is an equally contentious term to define, the most apropos for this text is the one adopted by Thomas Dye (2008): that public policy is everything that a government does and does not do. It is that vast body of rules, regulations, laws, and negotiations that surrounds our everyday. Policy professionals are primarily advisors, analysts, advocates, or organizers who are experts in the process of policy making (and unmaking). Sometimes they are also experts in a particular policy area, i.e. water quality or animal rights.

"Planning" is a type of public policy – one that focuses on the local and regional level, primarily on physical, spatial, and environmental issues. To make this more confusing, "planning" is also defined as a large-scale version of architecture; architects who design multiple buildings and street systems are doing planning.

As a graduate student at the University of Massachusetts, Amherst, I was welcomed by Dr. John Mullin into this field of urban, city, regional, and community planning. He concisely and quite elegantly captured the discipline in a pithy definition, which I have only slightly adjusted: *Planning is a place-based, future-oriented activity to guide community change, involving the setting of goals and means to achieve those goals, derived through some level of public involvement*. If that is not clear, then you now hopefully see what John Friedmann (1996) was only half-joking about when he himself began wading into the contested terrain of defining a field. Fortunately, you have the remainder of this book to learn more about urban planning – a compendium of stories about the work of professional planners past and present.

These planners pay close attention to the physical spaces that comprise human settlements and the design of cities, suburbs, towns, and rural areas. Very little of this book will grapple with the indoor experience – how people are impacted by the rooms they are in, the colors of walls, the furniture, etc. While there is ample research on the social, environmental, and psychological dimensions of interiors, I will leave those details to the burgeoning space architecture field (Howe and Sherwood 2000; Donoghue 2016). The focus of this book is instead on urban planning and design, meaning that we are

principally looking at the public realm – the exterior appearances of buildings, the outdoor rooms or parks and plazas created by the arrangement of buildings, the streets, byways, and sidewalks people traverse to get from one place to another. This is the work of urban planning.

The next chapter will take a trip back in human history, considering what a Mars colonization effort might learn from human colonization of various regions right here on Earth. The horrors of European colonization of Africa, the Americas, and Asia have been well documented. In addition, often dispiriting colonization and city-building efforts by China, the U.S., and the U.K. are also explored. For this book, the most salient lessons from those experiences are extracted and then compared with what we know about urban planning and design today. What does it mean to create human settlements on Earth that are successful? How do we even measure success?

Embedded in this history is the larger theme of challenging climates. What is the state-of-the-art around city planning in Antarctica, Siberia, and the Arctic Circle? The most inhospitable places on Earth appear to be tropical paradises compared to Mars' best locales.

Between the history and the review of best practices in urban planning today, along with a brief introduction to the climate, topography, and environmental conditions on Mars, I introduce a series of principles for the design of settlements on Mars. Across residential, commercial, industrial, and infrastructure dimensions, the book adds to and informs the current planning underway to colonize Mars. The most exciting element comes next: those principles are brought to life in both a conceptual and a rendered plan for the first city on Mars, tentatively named Aleph. With detailed drawings and diagrams, the layout, design, and conditions of human habitation and life on Mars become a reality.

You may be wondering whether such a reality is even desirable. Many critics have voiced reservations about the entire Mars colonization endeavor (Billings 2017; Szocik 2019). One common refrain was articulated by Rayna Elizabeth Slobodian (2015) who wrote that "...the rush to settle [Mars] is dangerous and careless," expressing deep concern about the real risks associated with colonizing Mars (p. 89). Others feel that the occupation of another planet simply turns humankind's attention away from caring for Earth and all of its problems (Billings 2017).

Aerospace scientist and writer Erik Seedhouse (2009) offered a different take:

> People argue that we have to solve the problems on Earth before we spend money on space. Such people are in need of a reality check because in five hun-

> dred or a thousand years, we are still going to be talking about the problems that need to be solved, and to think that the human race can attain some utopian state where all problems will be solved is quite simply delusional. (p. 9)

While unnecessarily mean, I agree with Seedhouse. People are explorers by nature; we have spread across every continent on Earth and have been traversing her oceans since the dawn of civilization. Should humans go to Mars? Probably not. Will we? Most definitely. Given that, I see my role as an urban planner to assist those who are heading there. I can help them be successful, thrive, and create places that endure. A cynic might argue otherwise and tell me that I shouldn't help and instead let them fail miserably. I disagree and am passionate about ways that urban planning can aid this extraordinary mission, a mission that will be quite dangerous and, in some ways, reckless. But good planning and good design can mean that when the Mars colonizers arrive, they will have the best chance possible of surviving and prospering. If this book contributes to that kind of outcome, I will be pleased.

Acclaimed space architect Brent Sherwood has written extensively on these questions, particularly around notions of lunar urbanism. He makes his case for his own work, and by logical inference, this book, through three major arguments. Sherwood (2009) begins by asserting that after Project Apollo (1969–1972) made exploration of other planets possible, humans will always be seeking to colonize space and we had better be ready. Next, he points out that the professionals largely involved today in shaping plans for future settlements are either 1) engineers who know little about architecture or planning, or 2) architects who know little about engineering. Because future off-world "planners will have to be well versed in both" disciplines in order to be successful, he argues that we ought to use the time now to build new fields of space architecture and urbanism (to which this book is seeking to contribute) (p. 317). Lastly, Sherwood insists that goal-setting early on is critical to "guide the paths that bridge present thinking to future history", believing firmly that "recognizing likely end-states of off-world urbanism might help avoid wasted efforts as that urbanism develops" (p. 317). For all of these reasons, the far-fetched and fantastical idea of cities on Mars becomes an important and serious object of scholarly attention. While certainly not happening anytime soon, Sherwood's thinking here is compelling: cities on Mars will happen at some point, so we should use the time we have beforehand to establish a new discipline at the intersection of space engineering and architecture/planning. The more well-thought out our goals for such cities are now, the more likely they will be successful – perhaps only in the distant future, but eventually.

What Is Mars Really Like?

One of the key objectives of this first chapter is to orient the reader to the basic atmospheric, geologic, topographic, and climatic features of Mars. This foundational knowledge will become essential as we proceed to Chapters 4-8, which examine the many dimensions of city design and building.

To begin with, Mars is only half the size of Earth, and its surface area is roughly the equivalent of Earth's land area (excluding the oceans) (NASA 2017) (see Figures 1.1 and 1.2). The Martian topography is quite diverse, hosting the tallest mountain in the Solar System, Olympus Mons, at 21.9 km, and depressions as deep as 8 km, like the crater Hellas Planitia (see Figures 1.3, 1.4, and 1.5).

The Red Planet's smaller size also means gravity is only 38% of Earth's, making it easier for anyone accustomed to Earth's gravity to jump high and run like an Olympic sprinter (NASA 2017). This difference in gravity played into Jerry Siegel's thinking when he developed the concept of an alien Superman, who grew up on a planet with much greater gravity than on Earth and the subsequent "super" powers he could display when arriving here (Andrae et al. 1983).

Like Earth, Mars' axis tilts (25 degrees compared to Earth's 23.5 degrees), meaning the Martian year is broken into four seasons (NASA 2017). However, these seasons are about twice as long as ours, given that one Martian year is the equivalent of 687 Earth days – not a surprise since Mars is so much farther from the Sun at 141 million miles, whereas the Earth is a mere 93 million away (NASA 2017).

Such distance means that Mars is a much colder place on average than Earth. Interestingly, surface temperatures vary greatly, reaching down to -190 degrees F at the poles during winter nights but getting up to a toasty 86 degrees F at the equator in the summer (Kozicka 2008, p. 20; Lewis et al. 1999, p. 24 and p. 185; NASA 2017) (see Figures 1.6 and 1.7). And with an atmosphere of primarily carbon dioxide, just a drop of oxygen, and more argon and nitrogen than you'd ever want to breathe in, the air on Mars is downright toxic to humans (Kozicka 2008, p. 19; Mahaffy et al. 2008). Moreover, the planet's atmospheric pressure is one-hundredth that of Earth (Piantadosi 2012).

Even with a steady Earth-like air supply, humans would not fare well prancing up and down the Martian landscape. The twin problems of Martian dust and radiation represent a major challenge to surface-level colonization (see Figures 1.8 and 1.9). With its thin atmosphere, the surface of Mars is exposed

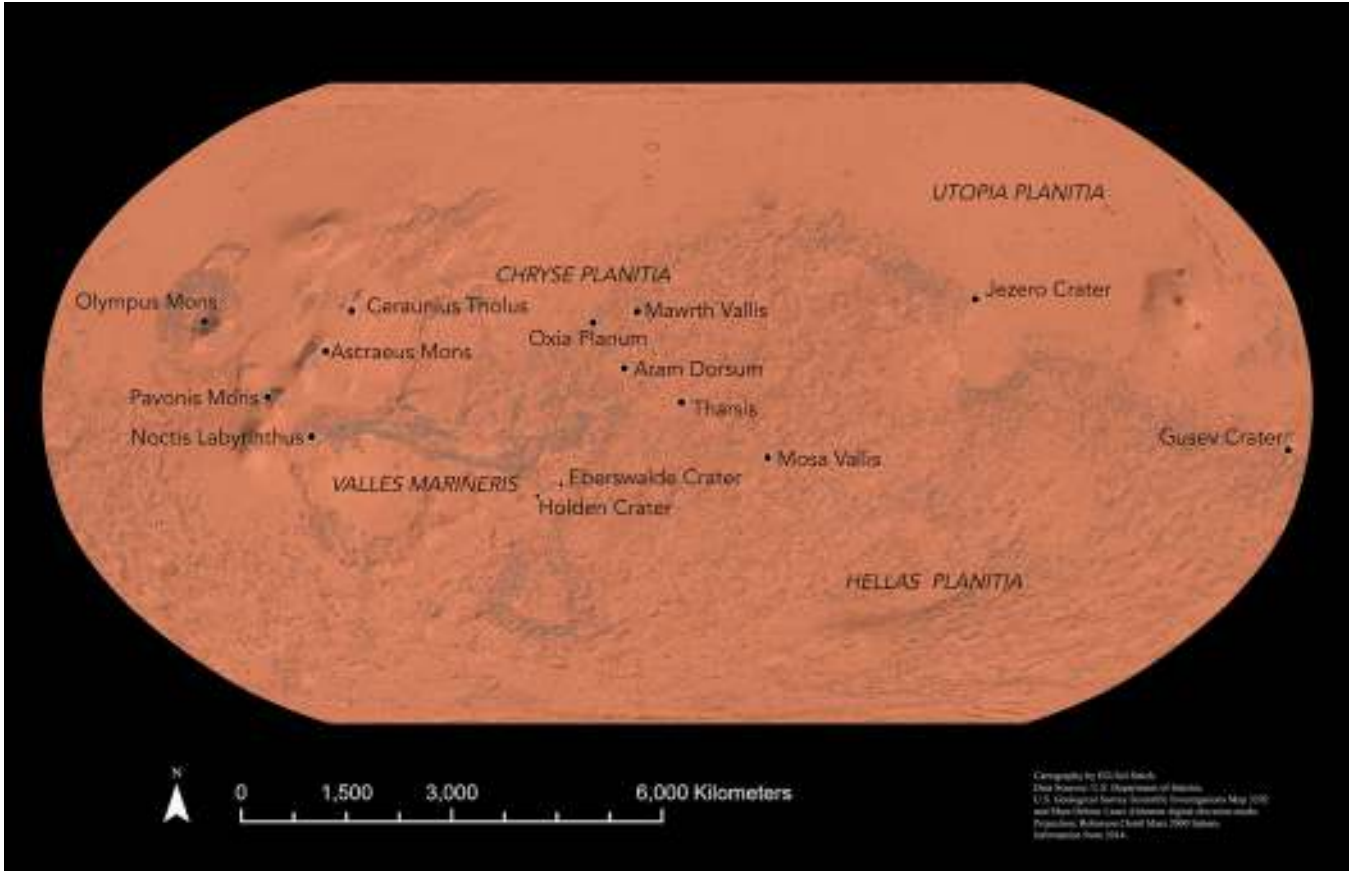

Figure 1.1: Map of Mars with labeled geographic features and regions (source: Elli Sol Strich).

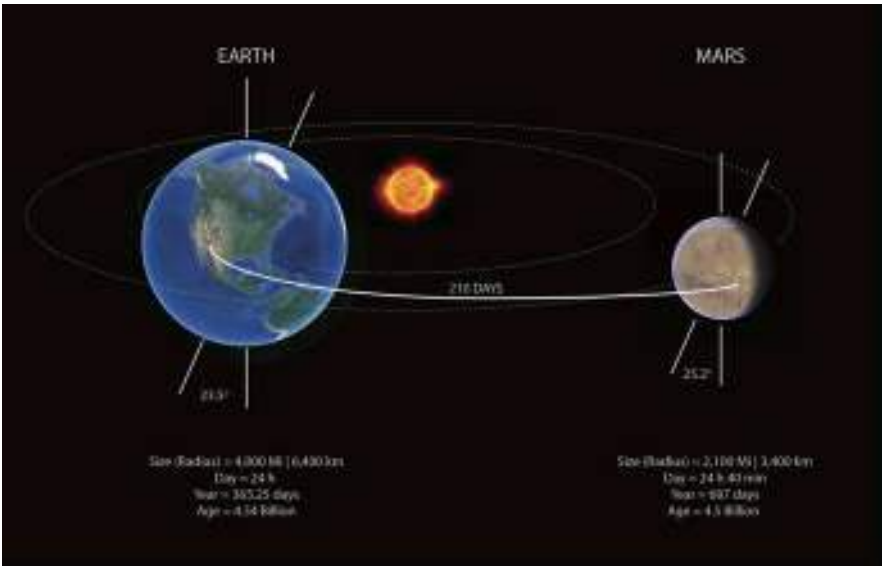

Figure 1.2: Comparison of Earth and Mars (source: Austin Raimond).

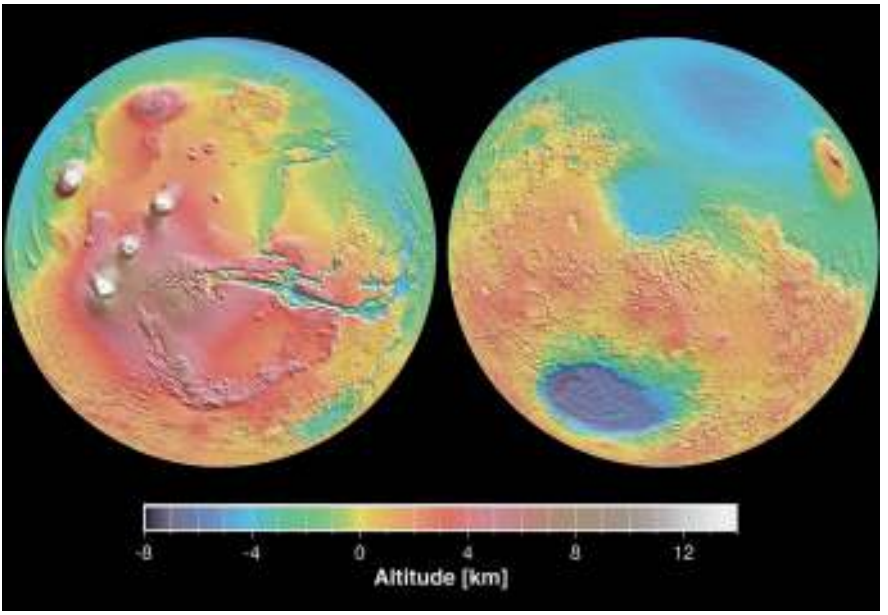

Figure 1.3: Topography of Mars (source: NASA/JPL).

Figure 1.4: Olympus Mons, the tallest mountain/volcano on Mars and in the entire Solar System (source: NASA/JPL).

to doses of radiation that are fatal to humans without protection (Kozicka 2008; NASA 2002; Simonsen et al. 1990). On Earth, people have found a multitude of ways to protect themselves when exposed to high levels of radiation, using lead, water, or concrete shielding (Häuplik-Meusburger and Bannova 2016). While Mars radiation is hazardous, protective measures can be developed, but unfortunately some of the equipment needed for such protection can be compromised by the ubiquitous red dust that swirls around the surface of the planet and kicks up when dust storms periodically descend (Piantadosi 2012). The good news is that like radiation, dust can also be managed and its risks mitigated.

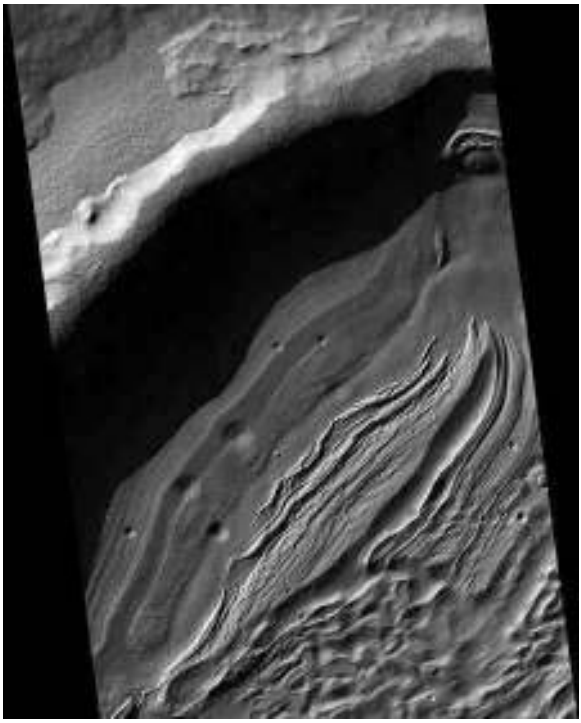

Figure 1.5: Hellas Planitia, the largest crater on Mars with a diameter of 2,250 km. This image shows a portion of the northwest quadrant of the crater (source: NASA/JPL-Caltech/University of Arizona/International Research School of Planetary Sciences).

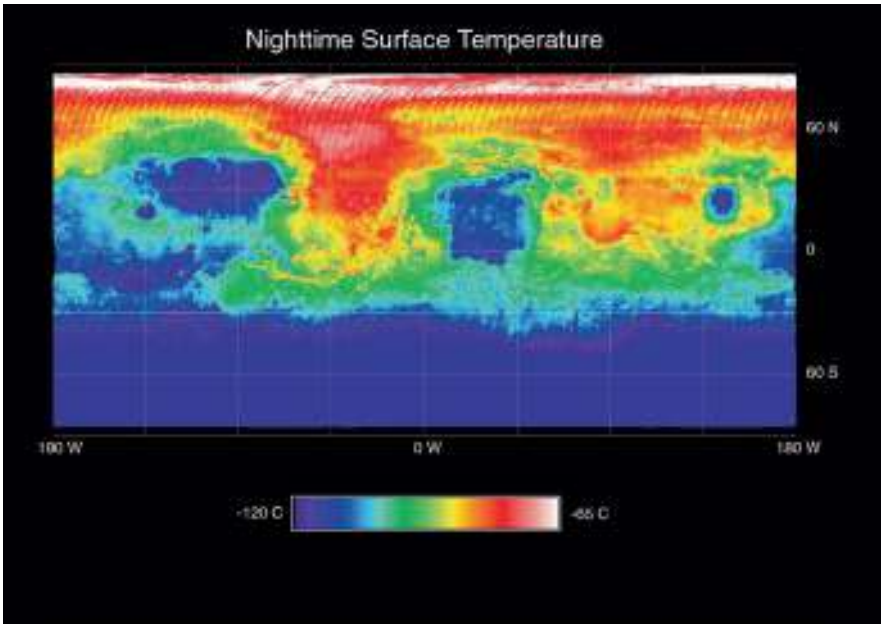

Figure 1.6: Nighttime surface temperature on Mars (source: NASA/JPL/ASU).

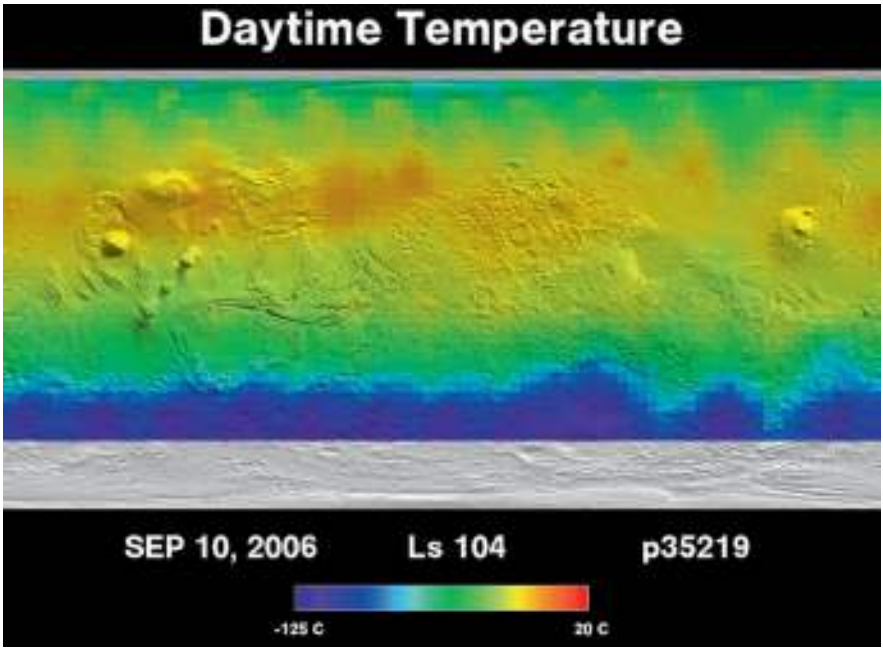

Figure 1.7: Daytime surface temperature on Mars (source: NASA/JPL/ASU).

Figure 1.8: The Martian landscape, view from Greenheugh Pediment (source: NASA/JPL-Caltech/MSSS).

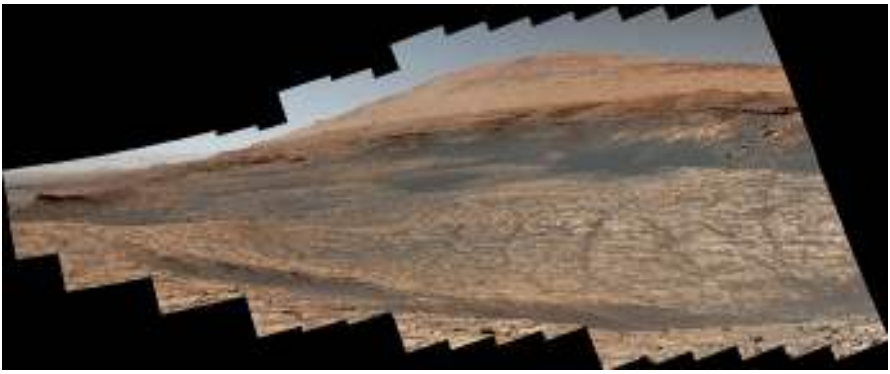

Figure 1.9: The Martian landscape, view of Mount Sharp (NASA/JPL-Caltech/MSSS).

Inspiration from Earth?

Humans have been building cities on our home planet for about 6,000–7,000 years. We have made plenty of mistakes to learn from (Wilson 2016) along the way. This book is built on the fundamental assumption that the insights, strategies, and best practices we apply today on this planet can be useful in settling Mars. Of course, not everything that we do in planning for cities on Earth translates to Mars: outdoor swimming pools, parks, or playgrounds may never exist, watershed planning has much less relevance on a planet without surface water, and air pollution polices will need to be rethought in light of a toxic atmosphere, just to name a few.

But the good news is there is much more that we *can* learn from the past and present, the state-of-the-art and the classic cases. The American Planning Association, the professional membership organization for the urban and regional planning community, in 2007 began identifying "Great Places" throughout the U.S. Through an open and competitive process, they solicit nominations and vet each to generate an annual list of unique neighborhoods, public spaces, and streets that demonstrate the ways that planning can improve communities. The process has identified and cataloged 290 places in every state in the country, showing the world with maps, diagrams, photos, and stories why these places matter and the role that planning played in creating them.

These Great Places may have some of those outdoor pools or flowing rivers that are impossible on Mars today, but it is possible to look beyond such details and learn from the larger pattern of success in planning. That is largely

the job of Chapters 4-8. They take what we know about city design and planning and consider in detail how such knowledge can be translated into the very different environment of Mars. A theme running throughout those chapters and the entirety of the book is that there is a dual source of principles that will guide Mars settlement: 1) the generalizable and universal history and practices of planning, and 2) the particular practices of planning in inhospitable environments.

While the tropical paradises of San Juan, Puerto Rico, or Manila, the Philippines might not resemble Mars, the rocky, frozen desert of McMurdo Station, Antarctica sure does. As do other remote, cold desert environments in Canada, Greenland, Iran, Turkey, and China, not to mention much of the Arctic Circle. While underpopulated compared to other parts of the world, these frozen deserts have been settled, and people live and work there. Throughout this book, reference will be made to these analogs, balancing insights from these locations with the broader lessons of urban planning writ large.

One particularly compelling thing about the Antarctic analog is that human settlements in and around the South Pole have in fact not been subjected to long-term urban planning. Noted novelist Kim Stanley Robinson described these places as "adhocitecture" – "a ramshackle and accidental assemblage of buildings without urban design" (as quoted in Daou and Gomez-Luque 2020, p. 174). No architects were even consulted in the first stages of building McMurdo Station; the settlement was not based on any kind of cohesive plan (Lawler 1985). There is much to learn from the Antarctica example, but perhaps Antarctica can also learn something from this book about Mars.

Organization of the Book

The following chapter gives some historical context to the monumental project of colonizing another world. Only a few hundred years ago, the Americas were viewed as a whole new world to Europeans, who spent months crossing an ocean (instead of outer space) to arrive at the shores of largely inhospitable lands in the Caribbean and Greenland. Surely, they had air to breathe, water to drink, and feared not for the radiation and dust storms a Martian colonist might fear, but they did have their own share of troubles, as the long list of failed settlements across North America shows (Reps 1992). Chapter 2 looks beyond the Americas and probes the devastating history of global colonization in order to discern key lessons for Martian colonists.

Chapter 3 then provides some much needed context for exploring and settling other worlds through a concise review of the milestones in the last seven decades of space exploration, with particular attention to the experience of architecture and planning off-world.

The following five chapters turn to the task of planning a city on Mars, drawing on the best research and scholarship to form a series of principles that can guide future planning. The first is very big picture and brings in psychology and neuroscience to present the First Principle of urban planning for Mars. Building on extensive research I have conducted over many years, this First Principle articulates the basic and sometimes primal needs humans have for the physical forms, shapes, and patterns around us. This First Principle is not Mars-specific, but needs to be expressed early on before getting into the weeds of city building and infrastructure.

The next four chapters examine transportation, residential, commercial, industrial, architectural, and non-transportation infrastructure dimensions of urban planning to discern additional key principles that should guide a future city on Mars. The principles are based on scientific, engineering, and social scientific consensus around the kinds of city planning solutions that could help overcome the unusual conditions on Mars. Many examples come from right here on Earth and draw heavily on hostile or challenging environments. Heefner (2020) argues that there is a long tradition in the military to use cold-climate locations to conduct research and prepare for extreme or unknown eventualities. Places like Thule Air Base in Greenland became proving grounds for new technology and approaches that could be transferrable into broader society. These extreme environments were "being presented as mid-way points between the known and the unknown of outer space" and were used to test out living and building techniques that could be employed on the Moon or beyond (Heefner 2020, p. 32).

The principles that emerge in Chapters 5, 6, 7 and 8 are derived from research in extreme environments, experimentation in outer space, lessons from robotic exploration of Mars, and general knowledge about what it takes to design and build cities on Earth. The principles are presented in a transparent manner, backed by strong empirical evidence that speaks directly to the Mars landscape, atmosphere, geology, and climate. Next, Chapter 9 reviews past published designs for Mars cities, considering serious scholarly attempts along with the scrawling of amateurs and the ruminations of former astronauts. Chapter 10 does the same thing for other non-Mars, off-world planning precedents, including schemes for settling low-Earth orbit, the Moon, and beyond. These precedent plans are then melded with the principles from

earlier chapters in Chapter 11 to form a detailed master plan for a prototype Martian City, called Aleph. The book concludes with some reflections on designing extraterrestrial cities more broadly and implications for life here on Earth.

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2

The History of Colonization (of Earth)

A book about the colonization of Mars demands at least a tacit engagement with the fraught concept of colonization itself. This chapter offers a glancing blow with the sad, cruel, and often disastrous history of how one nation sailed across seas or travelled over land to conquer another people and set up new settlements far from home. The very notion of colonization is regarded in contemporary scholarly circles in an abysmal light, and past colonization efforts are nearly universally criticized (Kohn and Reddy 2017; Tharoor 2016).

According to the seminal 20th century book *Colonization* by Albert Galloway (1908), colonization involves the "movement of population and extension of political power" from one place (colonizer) to another (colony), "when the sum of mutual relations…include[s] political dependence of the former upon the latter" (p. 1). Lloyd and Metzer (2013) provide an updated view of the concept, explaining how the phenomenon of colonization has been a "widespread phenomenon in human history not confined to any particular era, region, or continent" (p. 1) and fraught in its execution. Criticism of colonization is vast, even earning its own academic department at some institutions. Literally thousands of books and journal articles have been written that condemn the very thing that Galloway described, with particular attention to the devastation colonization has wrought upon indigenous people and their cultures, and the ways that colonization promoted and reinforced slavery and indentured servitude. The bulk of this criticism is levied at the colonial efforts that involved invading previously occupied lands, and the lessons from this dark chapter in human history cannot be lightly ignored. The settlement of Mars should benefit from an understanding of how colonization functioned and caused harm.

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J. B. Hollander, *The First City on Mars: An Urban Planner's Guide to Settling the Red Planet*, Springer Praxis Books, https://doi.org/10.1007/978-3-031-07528-5_2

In order to move the narrative of this book forward, the remainder of the chapter will examine the subject of colonization through a physical planning, urban design, and building perspective. Given that, perhaps "colonization" is not the best term here. "New town planning" may be more politically correct, though it does not sufficiently capture the distance our Mars explorers will need to travel and their remoteness when they arrive. "Settlement" might work on some level, as it is suggestive of the ruggedness of the new lands, but it does not imply the ways that a new Martian city would be initiated by and retain important connections to Earth. As such, "colonization" does in some way effectively describe the ambitions of Mars explorers – to create colonies on Mars that extend the language, culture, and morality of Earthlings.

Sticking with the colonization term and all its baggage might call into question the central mission behind this book. However, given the Red Planet's lack of a native human population to colonize, the fundamental moral bankruptcy of colonization should not apply here (Impey 2019).

An apt analog for colonization of Mars is the human settlement of Antarctica, a parallel I will return to often in these pages. When Europeans first landed on the Antarctic continent in 1821, there were no indigenous peoples living there (Gurney 2007). Average annual interior temperatures of negative 60 degrees Celsius make habitation there quite inhospitable (Australian Antarctic Division n.d.). The last century of scientific research and settlement building brought a sizable population of outsiders, building structures, airports, roads, and even retail stores and hydroponic gardens (McDaniel et al. 2012). While some critics have complained about the despoiling of a true frontier (Dodds 2006; Collis and Stevens 2007), few have drawn parallels with the broader history of colonization. Antarctica's planners have largely escaped the ire of post-colonial scholars, while at the same time they have benefited from our collective experience of settling new lands. The ways that Antarctica's settlements have been laid out, how infrastructure is designed, and the organization of land uses all draw on lessons from elsewhere. These lessons will be the subject of Chapters 4-8. The Antarctica experience has featured a collective embrace of the rule of law, democratic principles, and protection of human rights, thereby serving as a useful model for extraplanetary settlement (Dodds et al. 2017).

Historians have studied colonization thoroughly, producing innumerable volumes on the horrors of people conquering, subjugating, and enslaving other people. What is not as well studied are the mechanics of designing and building new settlements. In the remainder of this chapter, I take the reader on a limited tour of the world and abbreviated ride through history by

profiling four main epochs and geographies of colonization. For each, I provide some rudimentary context for the colonization effort and review the primary ways that each colonizer considered urban planning in approaching new cities and towns. I chose these four cases based on a thorough review of the colonization literature and my own familiarity with global history:

1. Ancient Greek and Roman colonization of the Mediterranean (900 BCE–400 CE)
2. Chinese colonization of East Asia (1000 BCE–800 CE)
3. British colonization of Oceania and the Eastern United States (1662 CE–1914 CE)
4. Spanish colonization of the Americas (1492 CE–1832 CE?)

These are by no means the most important cases. Instead, they were selected due to the rich literature available for each and their geographic and temporal variety. Other useful lessons may be inferred from additional cases, but these will provide at least some level of historical perspective for the remainder of the book, helping bind the principles to be developed in later chapters.

Ancient Greek and Roman Colonization of the Mediterranean

The Greeks and Romans are famed for their city building and colonizing activities. The expansion of those two civilizations was unparalleled in the Ancient world, and their practices continue to be relevant today. While a lot of factors were at work, the siting of these colonies appeared to be largely driven by access to water for both transportation and drinking (Sweetman 2011; Salmon 1970). Rome's first colonies were built along the Tyrrhenian coast in the fourth century BCE, and many more were built along rivers (Salomon 1970).

Beyond water access, the Greeks sought out other desirable characteristics. Odysseus himself recounted his thoughts on what makes an ideal location for a colony: "Deserted, a plethora of meadows flat enough to plow, dense forest, wild goats, a cove that served as a natural harbor, etc." (Wilson 2018). So it seems that even the 8th century BCE Greeks knew that uninhabited places are better than populated ones. Meadows for plowing are a theme this chapter will return to regularly; flat arable land was viewed by both the Greeks and Romans as central to any colony's agricultural success (Salmon 1970, p. 56).

The "dense forest" our hero refers to provides raw materials in the form of trees, rocks, leaves, and rich soil that settlers would need. The wild goats are presumably a source of food and animal labor, while the cove and harbor provide that crucial water access.

Omitted by Odysseus were the mining requirements of the time. As Tsetskhladze (2008) has written, colonies were often created with the express goal of establishing mining operations. The two northernmost Greek colonies, Pithekoussai and Cumae, were ostensibly settled because of their rich mining and other natural resources (Tsetskhladze 2008a, p. 245, also see Ridgway 1979). Likewise, archeological evidence in the form of locally minted gold coins shows that the Greek colony of Cyzicus had a gold mine (Boardman 1964, p. 254). Even after deciding on the general location of a new colony, the Greeks were highly cognizant of both proximity and access to mines when making decisions about a specific site selection (Tsetskhladze 2008b, p. 33 and p. 69). Mining would serve the local colony's needs, and more importantly satisfy Athens' growing demand for metals. A colony's close proximity to minerals would therefore have been equally as attractive as wild goats to a Greek city planner.

Once a site was selected, what did these ancient cities look like? What was their urban form? First off, they resembled their home cities; Aulus Gellius, writing about these colonies in 177 CE, said they "have the appearance of miniatures, and are reproductions of Rome herself" (Salmon 1970, p. 18; quoting *Noctes Attica*; Leofranc 1977). Rome began new colonies with 125-acre plots and later expanded their size as the population increased (Salmon 1970, p. 21), always building new colonies in pairs to allow for mutual support and to increase the overall likelihood of survival (Grimal 1983, p. 23). Likewise, the Greeks built colonies in networks, using the sea as a central hub that provided transportation linkages between the colonies (Malkin et al. 2013, p. 150). The intended population size of most colonies during the Roman Early Republic period (338–146 BCE) was between 4,000 and 6,000 persons, though population growth was accommodated by expansion (Salmon 1970).

In his book, the late renowned historian Edward Togo Salmon (1970) identified the city of Cosa (273 BCE) as a typical Roman colony, describing its urban form in detail. Sited 85 miles northwest of Rome on the flat portion atop a hill, Cosa has a port that connects via a channel to the sea. The city is encircled by walls that are six feet thick at the top and up to eight feet thick at the bottom. Inside the walls, a 300′ × 120′ plaza (*forum*) stretches along the main north-south road (*cardo maximus*), similar to what was found in most

Figure 2.1: The Roman forum and the comitium (source: unknown 19th century artist, from the book The Roman Forum: a topographical study by Francis Morgan Nichols / PD- US).

Greek colonies (Hayden 2013, p. 2). The forum is flanked by a government building (*basilica*) on one side and a religious temple, an open-air public meeting place (*comitium*), a local senate house (*curia*), and an amphitheater on the other side (see Figure 2.1). Another large road connected the entrance of the city to a fortified citadel, where a temple was placed to honor the Roman god Jupiter.

Other Roman cities introduced a secondary cross-sectional road (*decumanus maximus*) in their plans (Crawford 2006; Bradley and Wilson 2006). Larger cities introduced additional minor cardo and decumanus roads to form a grid pattern, which was also common in ancient Greek colonies (Figure 2.2). Locking onto the cardinal directions (north, south, east, and west) eased much of the survey work entailed in city design and building, though it ignored and literally paved over existing natural features in a landscape that would have benefited from a less rigid planning regime. The cardo maximus and decumanus maximus roads would also typically connect with other Roman settlements (Salmon 1970, p. 22).

By many measures, the people who lived in these cities flourished. The quarters were cramped, to be sure. The typical Greek house was a single square

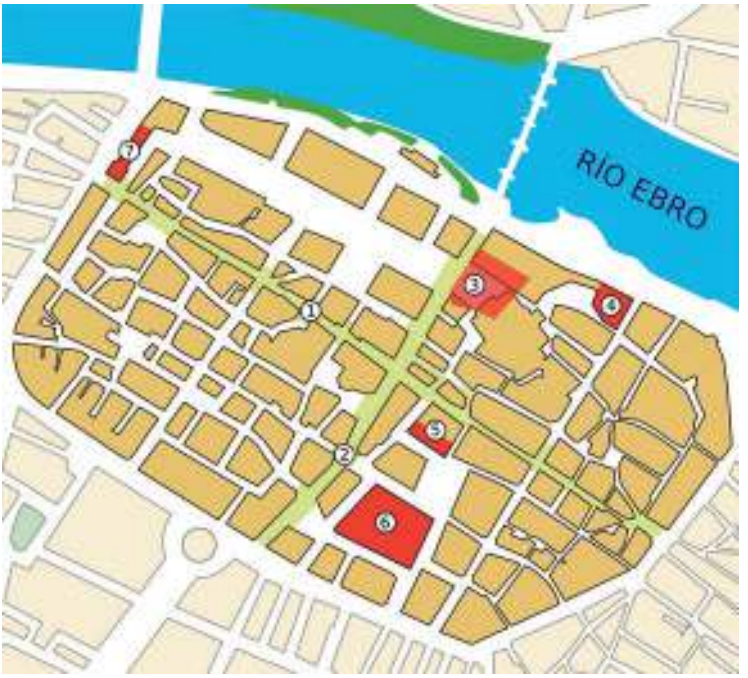

Figure 2.2: Grid pattern in the Roman city of Caesaraugusta (Legend: 1. Decumanus Road; 2. Cardo Road; 3. Caesaraugusta forum; 4. River port; 5. Public bathrooms; 6. Theater; 7. Wall) (source: Willtron / CC BY-SA 3.0).

room, 15 feet per side and built around an open courtyard (Ellis 2008; Hayden 2013). The average Roman house, the domus, was broken into several spaces for business and domestic use. It could be approached by entering an open area and then a peristyle court before passing into the rudimentary structure (Ellis 2008) (Figure 2.3). This luxury was reserved for the upper classes; peasants meanwhile had to settle for "wattle-and-daub huts with earth floors" (Ellis 2008, p. 11). These ancient homes were so small and cooking so dangerous that they often did not have kitchens (Clarke 1991, p. 25). The lower classes needed to eat at *tabernae*, small eating establishments along the public streets of an ancient Roman city (Clarke 1991, p. 25).

Mixed-use, relying on communal and group dining options, and small but with fluid indoor-outdoor spaces, these Greek and Roman homes have been widely emulated in some ways and eschewed in others the world over. Today, mixed-use housing continues to be popular in former countries of the Holy Roman Empire in Europe but uncommon in North America and Oceania (Hirt 2015). Beyond restaurants, other forms of communal and group dining are relatively uncommon globally, except for student dining halls and the

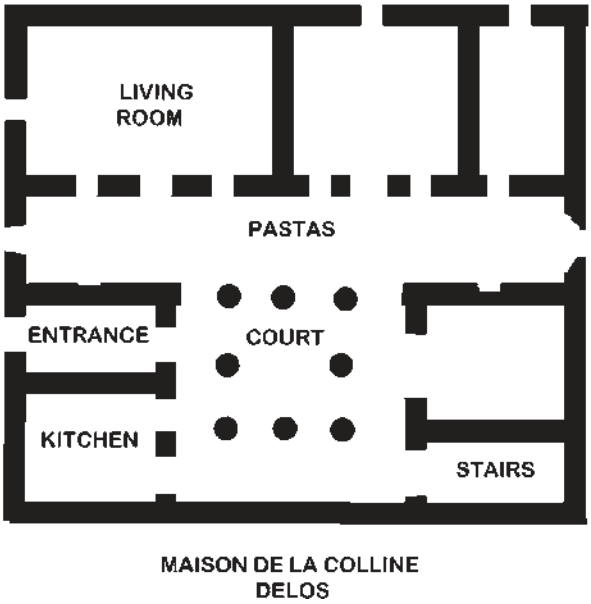

Figure 2.3: Interior plan of the House of Colline in 2nd century BC (source: Amandajm / Public Domain Mark 1.0).

occasional commune or kibbutz. But striking that balance between indoor and outdoor spaces remains a hallmark of modern city planning and architecture. Scholars have pointed to Frank Lloyd Wright's treatment of that very quality as a key element of his acclaim and success as an architect (Brooks 1979; Connors 1984). His landmark, Falling Water, was built in 1939, Pennsylvania. This single-family home was created around a waterfall, generating a striking fluidity between indoor and outdoor realms. Frank Lloyd Wright is also famous for his Richardson House in Buffalo, New York, where the distinction between outdoor patios and indoor living rooms can be hard to detect.

Public and religious structures were critically important in both Greek and Roman colonies (Malkin et al. 2013; Salmon 1970). The erection of impressive monuments spoke to the permanent nature of a settlement, and the use of imported materials, which was common for buildings like temples, communicated a colony's ties to its home city (Clarke 1991, p.88). According to Malkin et al. (2013), these temples and public buildings helped to legitimize the colonies and their success. In some ways, such investments could further feed that success by attracting greater market demand and increasing economic activity (p. 150).

Well after the publication of the *Odyssey* and the development of scores of Roman cities, noted Roman architect Vitruvius published his *Ten Books of Architecture* in 30 BCE. There, Vitruvius laid out a series of principles for architecture and city design, less focused on colonization and more on the abstract philosophy of designing places (Rowland and Howe 2001). A few key ideas are worth noting that were introduced earlier: 1) he required that the plaza (forum) be rectilinear in form and have a ratio of 3:2 length to width, 2) the plaza should be located near the water for a coastal city and at the center for inland cities, and 3) public buildings should be prominently placed around the plaza. Like many predecessors, Vitruvius advocated for a rigid street grid oriented along the lines of the prevailing winds (Rowland and Howe 2001).

Vitruvius' *Ten Book of Architecture* persisted for a long while and experienced a revival during the Renaissance, just as European powers were commencing their massive, global colonization of the Americas, Africa, and Oceania.

Chinese Colonization of East Asia

Chinese city planning goes back millennia to early dirt hut villages at the birth of the nation. But it really was not until the rise of the first imperial cities that those practices became routinized and regimented. Steinhardt (1990) shows how the Chinese sought to create new cities that were well protected, with high, thick surrounding walls and often encircled by a moat (p. 10), as well as rectilinear (often square) regularity in form (Wheatley 1971). Care was taken in city siting to ensure access to a good water supply and protection from excessive winds (Steinhardt 1990, p. 12), in addition to factors that might mitigate flood risks and potential attack from enemies. Important buildings were located close to the geometric center of a city and in capitals tended to be raised by platforms (Wheatley 1972, p. 185).

The *K'ao-kung Chi* is considered to be the earliest Chinese city planning text. It is a document embedded in *Liu-Hziang's Chou-Li*, written around 500 BCE (Wheatley 1972, p. 411). In planning out capitals, it called for an urban layout of a square, with three gateways on each side and nine avenues arrayed latitudinally and longitudinally (Wheatley 1972, p. 411) (Figure 2.4). The origins of this form derive from ancient Chinese notions of the universe, expressed in the concept of the *Magic Square*, known also as the mandala of Buddhism (Schinz 1996).

The significance of the Magic Square pattern was its harmonious combination of the basic forces of nature, yang and yin (Heaven and Earth). These

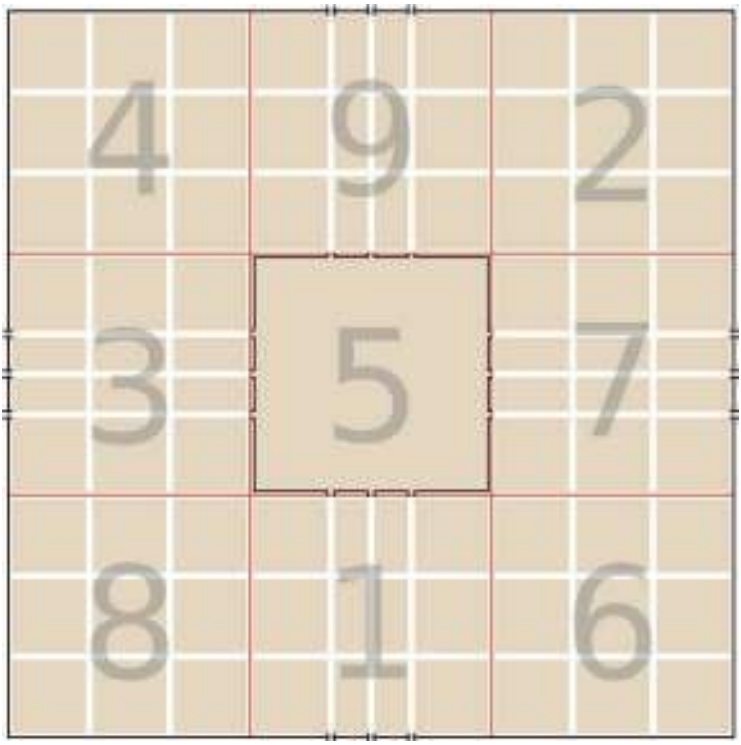

Figure 2.4: The Chengzhou street plan overlaid on a Luoshu (magic square) diagram (source: Lamassu Design Gurdjieff / CC BY-SA 3.0).

were represented by the geometric form of sacred numbers, with odd numbers being equivalent to the heavenly yang force and even numbers to the earthly yin force (Schinz 1996, p. 9).

The role of cosmo-magical forces was significant, and principles of feng-shui were widely adopted. Often, decisions about the removal of boulders or the planting of shrubbery were made to enhance the flow of chi (Wheatley 1972, p. 419). Alfred B. Hwangbo (1999), architecture professor at the Seoul National University of Technology in Korea, describes these concepts for a Western reader:

> Feng shui can be defined as a mélange of art and science which governs design issues of architecture and planning, embracing a wide range of disciplines of human interest… chi, the vital cosmic current which runs the universe and also means 'breath', can be scattered when it meets wind, and can be stopped when it meets water. (p. 191)

Like the Greek atom, chi was considered the most basic unit comprising everything in the universe, and city planners took great care in designing for it (Hwangbo 1999). So, it was not an accident that imperial cities were generously decorated with parks and gardens and were crossed with cardinally oriented north-south and east-west roads, all part of a larger effort to design for chi. Key uses in these cities included temples, altars, a Hall of Audience, and markets (Steinhardt 1990, p. 33). A main hall might be located on the north-south major road, whereas minor buildings could be found along the secondary east-west roads. Central ceremonial complexes were designed as a circle enclosing a square enclosing a circle enclosing yet another square, whereby the circle represents the heavens and the square represents humans (Steinhardt 1990, p. 68).

Other general directives spoke to issues like road width, the height of towers, and location of tombs for the dead. It was the *K'ao-kung Chi* (circa 500 BCE) and then the *Book of Documents* (aka Shu-Ching, circa 0 CE) that codified and consolidated Chinese wisdom around city planning and design. Emphasizing urban layout along cardinal directions, the Magic Square, and the centripetal symbolism of religious buildings, these texts provided a template for future city building in China and beyond (Wheatley 1972).

British Colonization of Oceania and the Eastern United States

For decades, the expression that "the sun never set on the British empire" was a reality. Stretching across Europe, Africa, Asia, Oceania, and North America, the British were accomplished colonizers. In 1662, with the passage of the Act for Building a Towne (Home 2011, p.11), the government created its first written laws dictating how new colonies were to be built. This legislation laid the groundwork for what was later called the Grand Modell in the Carolina colony (Wilson 2015, p. 12). Charles II and subsequent governments used this Grand Modell to insist that colonies be planned for in advance of their development, that they employ a square-mile grid form, that streets would be standardized regarding width and connectivity, and that sites would be reserved for both civic and commercial activities (Wilson 2015, p. 12; Home 2011, p. 8–9).

The Grand Modell was developed by Ashley Cooper, later Lord Shaftesbury. The Modell was unique in how it served as a constitution that "addressed social structure, political institutions, and physical design with equal

importance" (Wilson 2015, p. 8), an approach emulated by William Penn and James Ogelthorpe in Pennsylvania (1776) and Georgia (1733) respectively.

English administrators used the Grand Modell to guide new colony building throughout the British Empire. Wilson (2016) documents how the British required that new town sites be located on high ground, and that the layout of roads would consider prevailing winds (per Vitruvius). Specifically, these streets would generally have a dual hierarchy: main streets would be around 100 feet wide, while secondary streets would average 50 to 60 feet wide (Home 2011, 12). Plots of land were to be standardized in rectangular forms, to facilitate easy surveying, conveyance, and development (Home 2011, 16).[1] In this approach, planning was arranged for a range of purposes, including "infrastructure, aesthetics, health, economic development, social organization, and defense" (Wilson 2016, p. 14).

Philadelphia emerged from this same Grand Modell, though William Penn exerted key influence, attempting to create a "green country town", not a large, dense city. Penn sought to create a utopian town where homes were located on large lots, surrounded by gardens and orchards on all sides. A market, statehouse, and other civic buildings were to be located in the center of Philadelphia. Penn's original plan was revised a year later in 1682, adding additional density and the city's now-distinctive central open square and four outlying squares (Wilson 2015, 9) (see Figure 2.5).

While not evident in North American cities, the Grand Modell evolved in its implementation in Oceania, where reserved green belts surrounded each city, protecting it from the countryside. In the plan for Adelaide, Australia, a green belt encircled the city at a depth of between one and two miles, requiring all entrances to the city to be a park (Figure 2.6). A 19th century critic later reflected on this greenbelt plan, concluding "this would greatly contribute to the health and pleasure of the inhabitants; it would render the surrounding prospects beautiful, and give a magnificent appearance to a town, from whatever quarter viewed" (Maslen 1843, as quoted in Home 2011, p. 18).

Essential to the Grand Modell was access to water for both drinking and transportation, as well as location of new colonies on flat sites. In the 1904 Proceeding of the Royal Geographic Society of Australasia, William Light reported on his exercise to find a location for the new city of Adelaide:

[1] It was this hierarchy, regularity, and rectangularity that was emulated in other colonies and then formally adopted by the United States government after the Revolutionary War with the Land Ordinance of 1785. The Ordinance's impactful grid framework facilitated the easy surveying, subdivision, and development of land, in contrast with the British system, which relied on irregular, organic development in naturally occurring hubs and crossroads (Wilson 2016, p. 15).

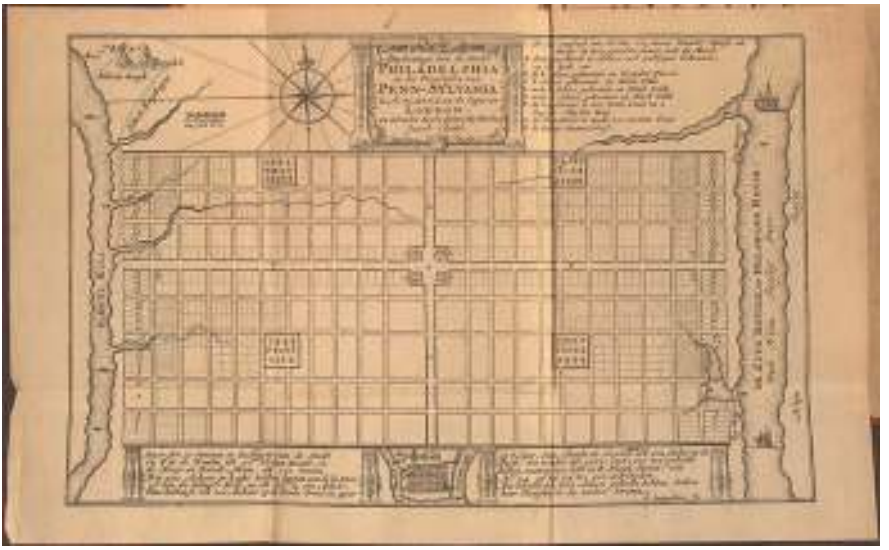

Figure 2.5: William Penn's 1682 plan for Philadelphia, Pennsylvania, USA (source: Library of Congress).

Figure 2.6: Present-day street map of Adelaide and North Adelaide (Peripitus / CC BY-SA 3.0).

> My first opinions with regard to this place became still more confirmed by this trip; having traversed over nearly six miles of a beautiful flat, I arrived at the river, and saw from this a continuation of the same plain for at least six miles more to the foot of the hills under Mount Lofty… affording an immense plain of level and advantageous ground for occupation. (Royal Geographic Society of Australasia 1904, p. 38)

Light was to consider topographic and geological features, and was also instructed to:

> …make the streets of ample width, and arrange them with reference to the convenience of the inhabitants and the beauty and salubrity of the town; and you will make the necessary reserves for squares, public walks, and quays. (Second Report of the Commissioners for the Colonisation of South Australia 1837, p. 34) (Brand 2006, p. 160–1)

This emphasis on street widths was a key factor in the plans for Sydney, Australia. Originally laid out as a penal colony, the city sought to transform itself for general populations in its 1802 plan. The straightening and widening of streets was performed for the express purpose of curbing "civil disobedience" (Brand 2006, 103). This use of street design to impact public order is part of a long tradition in city planning and is seen most clearly in Hausmann's famed 19th century redesign of Paris (Pinkney 1958). Hausmann converted the city's meandering medieval street network with a radial pattern that was aimed to prevent mobs from gathering strength; wide streets that met at rotaries might just prevent the kinds of rioting that occurred in Paris during the February Revolution of 1848.

A later Australia plan for the city of Wellington repeats many of the same Grand Modell ideals: a flat site near water, a gridiron street network, a concentration of public uses, and ample park and public space at 261 acres (Brand 2004, p. 111). The provision of so much public green spaces was a growing practice in British colonial planning into the 19th century, with the exception of the 1837 plan for Melbourne, Australia, where no formal public spaces were created (though formal open spaces were later developed on the city's fringes) (Priestley 1989).

More than any of the requirements set forth in the Grand Modell and incorporated into British colonial planning the world over, uncompromising attention was given to creating spiritually uplifting places. For example, in the plan for the new city of Auckland (New Zealand), the only building marked on the plan was a church (Brand 2006). A much earlier plan for New Haven,

Connecticut (U.S.) in 1638 made religion a centerpiece of the physical layout, much in the vein of the Chinese examples described earlier in this chapter. Wilson (2016) explained that the plan "linked the physical city to the spiritual city…combine[d] human-scale proportionality and civic space" and has "survived the centuries" (p. 5). Auckland and New Haven are not alone. English colonizers sought to connect people to these new lands beyond the corporeal experience of buildings, fields, and docks. For some, like Penn, that spirituality was multi-denominational and even had room for native peoples. For others, colonization was a chance to reinforce their singular religious worldview. Either way, the result was the use of physical forms to enhance and project a dimension of humanity that demanded attention: spirituality.

Spanish Colonization of the Americas

New Roman colony plans were codified into written documents and expressed well in Vitruvius' two-thousand-year-old *Ten Books of Architecture*. Chinese planning was captured in the *Book of Documents*, where rules and regulations for new colonies were laid out. And the British employed the Grand Modell to communicate the Crown's wishes for the physical planning of new settlements the world over. But it was the Spanish, arguably more so than any other nation in history, that so precisely accumulated and then published their collective wisdom around new town design (Reps 1965). The Law of the Indies (1573) was the high point in that Spanish success. The Law of the Indies "established uniform standards and procedures for planning of towns and their surrounding lands…" and was widely adopted by both Spanish colonizers and the planners in the United States and Mexico who followed (Reps 1965, p. 28). Reps (1965) goes on to explain this extraordinary impact: "Literally hundreds of communities in the Western Hemisphere were planned in conformity to these laws – a phenomenon unique in modern history" (p. 29).

As with the above examples in the Mediterranean, Asia, and Oceania, the Law of the Indies set out clear guidance for selecting a site for new colonies: an elevated location surrounded by land suitable for farming, access to a water supply, and near fuel and forest resources (Reps 1965).

The urban form expressed by the Spanish was unique from the other plans described earlier, as the plaza would be the central organizing area for the new town. Coastal cities would have their plazas along the shore, where inland cities' plazas would be in the center. The length of each plaza was prescribed to

be one and one-half times the width[2], at least 200 feet wide and 300 feet long and no greater than 800 feet long and 300 feet wide (Reps 1965). Like Greek, Roman, and Chinese planning, the Spanish required that the plaza be oriented around the cardinal directions. Unlike other planning schemes, the plaza was the origin point for four main streets stretching in each of these cardinal directions, with two minor streets stretching from each corner. Each of the main streets was covered by an arcade (Reps 1965) (Figs. 2.7 and 2.8). This emphasis on the experience of the pedestrian traveler and protection from the Sun and rain (arcades) and the winds (street orientation) was further reified in the Law of the Indies' requirements around construction, planting,

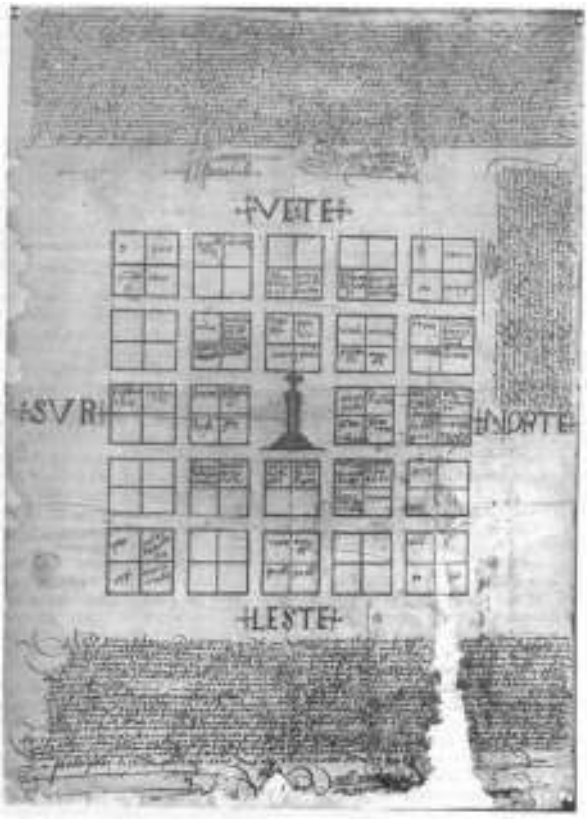

Figure 2.7: Founding plan of the City of the Resurrection (Mendoza, Argentina) with cardinal directions labeled in Spanish (R Torres Lanzas, reduction by General Archive of the Indies of Seville, uploaded by Federico Gomez Aghetta / CC BY 4.0).

[2] This 2:1 ratio has been observed in other societies and deserves further study in the next chapter.

Figure 2.8: Plaza of Mendoza, 1860 (source: P. Mousse, lithograph of a drawing by Pallière, Instituto Nacional Sanmartiniano / PD- ART).

and breeding, creating an orderly, consistent viewscape. "Settlers are to endeavor, as far as possible, to make all structures uniform, for the sake of the beauty of the town" (Law of the Indies, as quoted in Reps 1965, p. 30). Reps (1965) concluded in his analysis that "these regulations stand out as one of the most important documents in the history of urban development" (p. 30).

Planetary Preservation

In Kim Stanley Robinson's *Red Mars* trilogy, geologist Ann Clayborne leads a group that seeks to preserve Mars in its original condition, prior to human contact. She argues that there is much to learn from Mars and efforts to settle the planet threaten to erase some critical geological records. Summons et al. (2011) and other scholars have written on planetary preservation, identifying key environmental records that could be compromised by Martian colonization. No matter the nature of a human settlement of Mars, microbial contamination, CO2 emissions, and subsurface disruptions could all interfere with the ability of scientists to fully catalogue and understand the history and current environmental systems of the Red Planet.

Robinson skillfully portrays this debate in his novels by pitting Ann and her allies against the colonizers seeking to terraform Mars to make it more Earth-like and more comfortable for human life. In light of the colonization

history reviewed here, the arguments for planetary preservation are certainly salient. One scholar suggests a compromise in a proposal for a Martian-wide parks and wilderness network, hence allowing for colonization but protecting most of Mars from development (Cockell and Horneck 2004; Cockell and Horneck 2006).

Beyond protecting and preserving Mars, there also remain mysteries around the possibility of native life on Mars. While the little green men of 1950s science fiction appear extremely unlikely, scientists continue to investigate the more likely possibility of finding smaller microscopic life on Mars (Johnson 2020). If life on Mars does exist, then the history of colonization on Earth becomes highly relevant for future Mars settlements, since we must minimize our impact on any native life forms.

Lessons from History

Throughout human history and across Earth, people have sought out new lands to conquer and to settle. In this chapter, I have reviewed just a few cases to draw out lessons for the next great human endeavor: settling Mars. Ancient roads, decaying grand buildings, and fossilized artifacts all speak to the material record of planned towns and cities. But it is the written word that has spread even more efficiently, from the parchment paper of Rome to the printing presses of England, to today's bit and bytes across the Internet. It is in the written word that John Reps identified the Law of the Indies as a shaper of urban development like no other (p. 30). So as you read *these* words, the urban form of the yet-to-be-settled Mars can take shape.

The first chapter offered an introduction and non-technical survey of some of the important geologic, atmospheric, and climatic conditions of Mars – certainly a prerequisite to any serious plan for Martian colonization. This chapter serves an equally essential function, providing historical perspective. By looking back, we can learn from the past and draw lessons that can be applied to the settlement of Mars. What follows is a concise articulation of lessons from the cases studied and from the broader colonization literature. Combined with the principles presented in Chapters 4-8, these lessons will serve as the backbone for the settlement plan presented in Chapter 11.

1. New Town Site Selection: ideally, flat sites with access to drinking water, transportation, and proximate natural resources (e.g. mining and forests).
2. Street Design: climate considerations (e.g. wind) should drive the layout and configuration of streets; connectivity is paramount.

3. Public Spaces: centrally located public gathering spaces are essential; access to sunlight and greenery should be integrated.
4. Prominent Public Building: in or close to the central public gathering spaces should be reserved a location for important public buildings, including governmental and market uses.
5. Spirituality: the form, uses, and design of the settlement should consider metaphysical dimensions.

Together, these lessons can help Martian planners avoid past mistakes, learn from what worked, and increase the likelihood that colonies will thrive and flourish.

One of the English planners introduced earlier in the chapter, James Ogelthorpe, was heavily influenced by Renaissance writer Niccolo Machiavelli. Of course, Machiavelli is best known for *The Prince* (1513), a largely amoral exposition on how the state can abuse its power and manipulate others. It may therefore be interesting to learn that his ideas and writing were quite expansive and included ruminations on urban planning and design. In one of Machiavelli's great treatises on society, *Discourses on the Ten Books of Titus Livy* (1517), he explored the idea of *traslatio virtutis*, translated by Wilson (2015) as "virtuous societies spring up in new lands as corrupting influences consume older nations" (p. 8). Machiavelli, and arguably Ogelthorpe and generations of subsequent planners, sought to use the opportunity presented by colonization to jettison the "corrupting influences" of their homes, dreaming of new, virtuous societies in new lands – albeit at the expense of colonized peoples. My brief review here of the history of global colonization was hardly an evaluation of virtuosity, but this utopian bent should feel familiar. The concept of *traslatio virtutis* is aspirational, but planners of the past have faced concrete challenges, and we should heed these lessons from history as we explore the prospects for settling Mars.

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3

Lessons from Seven Decades of Space Exploration

We have been a busy species. Nowadays, there are few spots on Earth where people have not already built sizable cities and towns. From Baffin Island in the Arctic to the swamps of the Bayou of Louisiana (USA), from the desert savannas of Africa to the Falkland Islands off the tip of South America, we have spread far and wide across the planet, settling just about every shore, every hill, and every peninsula.

Chapter 2 offered a sweeping account of this settlement through the lens of colonization. One society, settled and wealthy, seeks out greater fortune, power, and adventure through the conquest of distant lands. The parallels to human settlement of Mars are not exact, but the lessons from the colonization of Earth do offer much to inform Martian settlement.

Mars, however, is not the first off-Earth locale that people have set their eyes on for colonization. We have been travelling beyond our planet now for seven decades, settling low-Earth orbit through the International Space Station (ISS) and visiting the Moon. The ISS just recently celebrated two decades of continuous human presence, a marker of off-world colonization unlike anything else. While not large, the ISS has accommodated up to 13 persons at a time, and individuals have lived there for up to a year. There is much to learn from this colonization of low-Earth orbit, and this chapter will examine the history of the ISS and what Martian settlement might learn from these experiences.

The human presence on the Moon was brief and fleeting, but probes and spacecraft have been visiting regularly for decades. More importantly, several space agencies have detailed plans for a long-term human presence on the Moon. These plans will be reviewed in this chapter, as well as previous studies

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J. B. Hollander, *The First City on Mars: An Urban Planner's Guide to Settling the Red Planet*,
Springer Praxis Books, https://doi.org/10.1007/978-3-031-07528-5_3

of the Moon and its suitability to support human life. While Martian settlement is a long-term prospect, some experts predict a human colony on the Moon before the end of the 2020s (Zubrin 2014).

Our explorations have gone way beyond low-Earth orbit and the Moon. Humans have sent spacecraft to asteroids and comets, to the moons of Saturn, to Pluto and beyond to interstellar space. While the aims of these missions have largely been in pursuit of scientific understanding, NASA and other space agencies have serious plans in the works to put people in semi-permanent dwellings far beyond the Moon. I will discuss these efforts and their relevance for Mars.

The efforts of space explorers are based upon solid science and engineering knowledge – the critical tools and techniques that we have today that can be put into place to build a city on Mars. In this chapter, I will also discuss these technologies, where they have already been used and how. Next, I will turn to those missing pieces, answering the question: what is it that we have not yet mastered in order to settle Mars?

The chapter ends by reviewing the possible timing of a Martian settlement, comparing estimates across space agencies, scientists, and space engineers to explore how soon we might have a city on Mars. Lastly, with that timetable in hand, the chapter speculates on what other off-Earth settlements might exist at the time of a Martian city-building effort, and how those other settlements might play a role in a larger system of space colonies.

A Brief History of Off-World Exploration

After millennia of staring into the vast night skies, in 1957 the Soviet Union launched Sputnik 1 into space and forever changed history. The Soviets landed the first spacecraft on the Moon two years later, then launched the first human into orbit (1961), followed by the first spacewalk (1965). The Space Race was on, and the United States soon began marking its own firsts, including the first people to orbit the Moon (1968) and the first humans to land on the Moon (1969) (see Table 3.1).

In the years that followed, the U.S. and the Soviet Union sent probes and spacecraft deep into the Solar System, orbiting and landing numerous craft on asteroids, comets, Mars, and the moons of other planets. In the 2000s, Europe, Japan, and China developed their own advanced space programs. Since then India, the United Arab Emirates, and Israel have also joined in developing and launching spacecraft.

Table 3.1 Overview of relevant milestones in space exploration ("Space Exploration – Major Milestones" n.d.)

Launch date	Name	Country	Notes
1957	Sputnik 1	USSR	First satellite launched from Earth.
1959	Luna 2	USSR	First spacecraft to land on the Moon.
1961	Yury Gagarin from Vostok 1	USSR	First human to orbit Earth.
1965	Aleksey Leonov from Voskhod 2	USSR	First spacewalk.
1964	Mariner 4	US	First spacecraft to capture images of Mars.
1968	William Anders, Frank Borman, and James Lovell from Apollo 8	US	First humans to orbit the Moon.
1969	Neil Armstrong from Apollo 11	US	First human to land on and walk on the Moon.
1970	Luna 16	USSR	First lunar samples collected and delivered to Earth.
1971	Salyut 1	USSR	First space station launched.
1971	Mariner 9	US	First spacecraft to orbit Mars.
1971	Mars 3	USSR	First spacecraft to land on Mars.
1976	Viking 1	US	First photos sent from the surface of Mars to Earth.
1981	Colombia	US	First reusable spacecraft (launched and returned)
1990	Hubble Space Telescope	US and European Space Agency	First large space telescope launched
2000	Sergey Krikalyov, William Shepherd, and Yury Gidzenko	US	First crew to remain on the ISS for an extended period of time.
2000	NEAR on asteroid EROS	US	First spacecraft to orbit an asteroid.
2001	NEAR on asteroid EROS	US	First spacecraft to land on an asteroid.
2005	Cassini-Huygens spacecraft, Huygens probe	US, European Space Agency, Italy	First spacecraft to land on the moon on another planet (Saturn's Titan).
2010	Hayabusa	Japan	First samples of an asteroid collected and sent back to Earth.
2014	Rosetta	European Space Agency	First spacecraft to orbit a comet
2014	Philae	European Space Agency	First spacecraft to land on a comet
2019	Chang'e	China	First spacecraft to land on the far side of the Moon.

Source: Alyssa Eakman

Through scores of missions, these spacefarers have studied faraway places and brought back untold volumes of knowledge about space and a variety of heavenly bodies. For this book, it is worth highlighting those missions with an explicit focus on Mars (see Tables 3.2, 3.3, and 3.4). Of the 49 Mars launches from Earth since 1960, 22 successfully landed, 11 were successful flybys, and 16 failed.

Table 3.2 Historical log of successful Mars landings (mars.nasa.gov n.d.)

Launch date	Name	Country	Notes
1971	Mars 3 Orbiter/Lander	USSR	Orbiter obtained approximately 8 months of data and lander landed safely, but only 20 seconds of data
1971	Mariner 9	US	Returned 7,329 images
1973	Mars 5	USSR	Returned 60 images; only lasted 9 days
1973	Mars 6 Orbiter/Lander	USSR	Occultation experiment produced data and Lander failure on descent
1975	Viking 1 Orbiter/Lander	US	Located landing site for Lander and first successful landing on Mars
1975	Viking 2 Orbiter/Lander	US	Returned 16,000 images and extensive atmospheric data and soil experiments
1996	Mars Global Surveyor	US	More images than all Mars Missions
1996	Mars Pathfinder	US	Technology experiment lasting 5 times longer than warranty
2001	Mars Odyssey	US	High resolution images of Mars
2003	Mars Express Orbiter/ Beagle 2 Lander	ESA	Orbiter imaging Mars in detail and lander lost on arrival
2003	Mars Exploration Rover – Spirit	US	Operating lifetime of more than 15 times original warranty
2003	Mars Exploration Rover – Opportunity	US	Operating lifetime of more than 15 times original warranty
2005	Mars Reconnaissance Orbiter	US	Returned more than 26 terabits of data (more than all other Mars missions combined)
2007	Phoenix Mars Lander	US	Returned more than 25 gigabits of data
2011	Mars Science Laboratory	US	Exploring Mars' habitability
2013	Mars Atmosphere and Volatile Evolution	US	Studying the Martian atmosphere
2013	Mars Orbiter Mission (MOM)	India	Develop interplanetary technologies and explore Mars' surface features, mineralogy and atmosphere.
2016	ExoMars Orbiter/ Schiaparelli EDL Demo Lander	ESA/ Russia	Orbiter studying Martian atmosphere and EDL demo lander lost on arrival
2018	Mars InSight Lander	US	Landed on Mars November 2018.
2021	Perseverance Rover	US	Successful landing in April 2021
2020	Tianwen-1	China	Successful landing in May 2021.

Source: Alyssa Eakman

Table 3.3 Historical log of Mars Flybys (mars.nasa.gov n.d.)

Launch Date	Name	Country	Result	Notes
1960	Korabl 4	USSR	Failure	Didn't reach Earth orbit
1960	Korabl 5	USSR	Failure	Didn't reach Earth orbit
1962	Korabl 11	USSR	Failure	Earth orbit only; spacecraft broke apart
1962	Mars 1	USSR	Failure	Radio Failed
1962	Korabl 13	USSR	Failure	Earth orbit only; spacecraft broke apart
1964	Mariner 3	US	Failure	Shroud failed to jettison
1964	Zond 2	USSR	Failure	Radio failed
1964	Mariner 4	US	Success	Returned 21 images
1969	Mariner 6	US	Success	Returned 75 images
1969	Mariner 7	US	Success	Returned 126 images
2020	Tianwen-1 Camera	China	Success	Flyby sucessful
2020	Emirates Mars Mission	United Arab Emirates	Success	Flyby successful

Source: Alyssa Eakman

Table 3.4 Historical log of failed Mars missions (mars.nasa.gov n.d.)

Launch Date	Name	Country	Notes
1969	Mars 1969A	USSR	Launch vehicle failure
1969	Mars 1969B	USSR	Launch vehicle failure
1971	Mariner 8	US	Flew past Mars
1971	Kosmos 419	USSR	Missed planet; now in solar orbit.
1971	Mars 2 Orbiter/ Lander	USSR	Lost en route to Mars
1973	Mars 4	USSR	Lost near Phobos
1973	Mars 7 Lander	USSR	Lost prior to Mars arrival
1988	Phobos 1 Orbiter	USSR	Launch vehicle failure
1988	Phobos 2 Orbiter/ Lander	USSR	No orbit insertion; fuel problems
1992	Mars Observer	US	Lost on arrival
1996	Mars 96	Russia	Lost on arrival
1998	Nozomi	Japan	Lost on arrival (carried on Mars Polar Lander)
1998	Mars Climate Orbiter	US	Stranded in Earth orbit
1999	Mars Polar Lander	US	Flew past Mars
1999	Deep Space 2 Probes (2)	US	Missed planet; now in solar orbit.
2011	Phobos-Grunt/ Yinghuo-1	Russia/ China	Lost en route to Mars

Source: Alyssa Eakman

Early successful missions captured amazing images of the Martian planet, debunking fantasies about advanced Martian civilizations and their vast canal networks.[1] The first pictures of the barren Martian landscape captured by Mariner 4 were shocking to a public hopeful for what Mars might be. Ray Bradbury's *Martian Chronicles*, published first as a series of short stories and then as a book in 1950, had captured the public mood in those years leading up to Mariner 4 and what it might be like for humans to live on Mars.

Those images from Mars, and then additional pictures to follow in the 1960s and 1970s, showed a planet that seemed wholly uninhabited and likely uninhabitable. The first human-created machine to land on Mars, Viking 2, sent back images in 1976 of an empty, desolate, and rocky land (see Figures 3.1 and 3.2). Norman Horowitz (1915–2005), astrobiologist at the Jet Propulsion Laboratories, concluded at the time that the "planet was devoid of water and suffused with cosmic galactic rays, both of which were sufficiently sterilizing" (Johnson 2020, p. 71).

Only in the 1990s with the Mars Global Surveyor and Pathfinder, and then the Odyssey, Spirit, and Opportunity landers in the 2000s, did the potential for life on Mars begin to appear. The explosion of new science about Mars' geology, chemistry, and possible biology has reinvigorated Earthlings' interest in the Red Planet as a place where life may have existed, may still exist on some level, or can someday exist. Recent research has suggested that liquid water may exist on Mars, with some even arguing that vast oceans are present below the surface (Ojha et al. 2015; Johnson 2020).

Figure 3.1: Viking 2 first sent home this image of the rocky Martian terrain, with a peak at its own landing footpad just after touchdown on September 3, 1976 (source: NASA/JPL).

[1] In the 19th century, Percival Lowell famously documented a series of what he believed were canals on Mars. Spacecraft returned images in the 1960s that seemed instead to show that what appeared as lines or canals were just a series of closely laid specks or dots on Lowell's low-resolution images (Johnson 2020).

Figure 3.2: Two days after landing on Mars, Viking 2 sent home this, the first ever color image of Mars (source: NASA/JPL-Caltech).

With all of this Mars fever, it is important to not lose sight of the broader human opportunities for Solar System exploration. Sherwood (2016) introduced a useful framework to consider what he calls the "human-accessible" Solar System (see Figure 3.3). He wanted to establish a map for humans to utilize when venturing away from our home planet, writing, "nothing builders have faced in the most recent ten millennia of human history – recorded in artifacts – exactly prepares us for this new challenge" (p. 35). Since people were going to continue to explore beyond the Earth, they should learn to appreciate the possibilities for each type of environment across the dimensions of current capabilities, space radiation, remote control, long-distance journeys, and landing/surface operations. The L1–L5 designations in Sherwood's diagram require a bit of explanation.

Like all celestial body systems, the Earth-Moon system is comprised of Lagrange or libration points (see example in Figure 3.4). In thinking about these Lagrange points, it is useful to consider L1 first: the two gravitational forces of the Earth and Moon are opposite one another, one falling and one rising in strength, so L1 is that point where the two gravitational forces are equal.

For the Earth-Moon system, each Lagrange point has its unique advantages and disadvantages for possible human habitation. As Sherwood (2016) points out, L1 could be a useful midway staging point for travel between the Moon and beyond, while L2 is positioned to best facilitate communications between the Earth and the far side of the Moon.

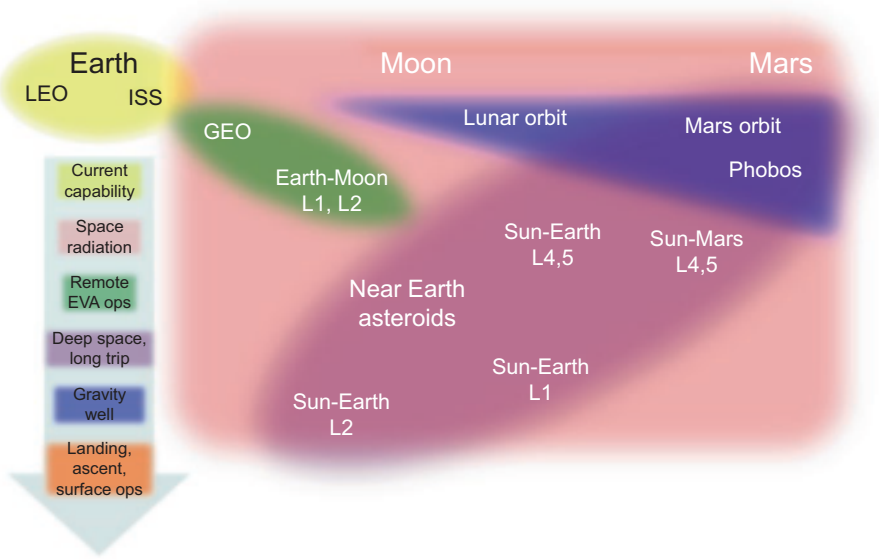

Figure 3.3: Map of the "human-accessible" Solar System. GEO = geosynchronous orbit (the present location of telecommunications and global positioning system satellites). LEO = low earth orbit. ISS = International Space Station. L1–L5 = Lagrange or libration points (source: Sherwood 2016, in Häuplik-Meusburger and Bannova 2016).

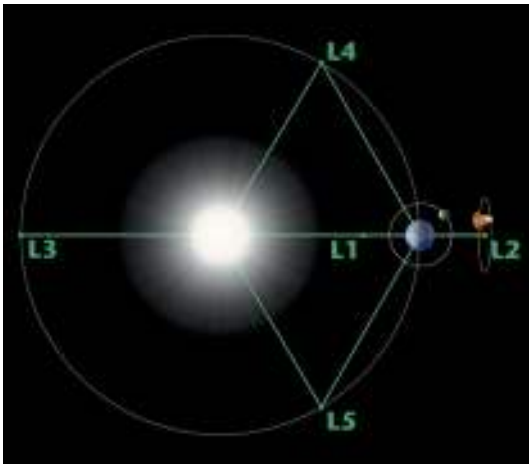

Figure 3.4: Diagram of five Earth-Sun Lagrange points (source: NASA/WMAP Science Team).

The remainder of the chapter will discuss the actual and planned human settlement activities in Sherwood's regions, providing the kind of overview needed before the remainder of the book tackles the specific geography of Mars. These other human-accessible locales will again emerge in Chapters 9

and 10, preceding my presentation of a detailed plan for a Martian city. In Chapter 9, precedents for planning a Martian city are presented in detail, and Chapter 10 offers a detailed review of such precedents for other non-Martian off-world urban plans. Together, these two chapters offer an extension of historical accomplishments and realistic near-term plans, tapping into the imagination of writers, filmmakers, artists, and scientists. In those chapters, I review some of the biggest and boldest ideas people have come up with to colonize the Solar System.

Architecture and Urban Planning on the International Space Station

Taking 11 years to complete, the International Space Station remains one of the greatest achievements of humankind. Coming together across borders, five nations (the United States, Canada, Russia, Europe, and Japan) collaborated on this endeavor, dwarfing previous wonders of the world. Building a space station that orbits Earth at 7,500 mph (28,000 km/h) at approximately 250 miles (400 km) above the surface of the Earth took extraordinary engineering skills. I have some experience with construction here on Earth and know firsthand how challenging it is to build even a simple home or retail building, with the scores of specialized professions involved (electricians, structural engineers, plumbers, etc.), the need to schedule activities in certain sequences, difficulties with coordination and communication, and access to building materials and specialized equipment. It is amazing to think about how the scientific leaders of five countries were able to overcome these hurdles and complete the ISS in low-Earth orbit in such little time (see Figure 3.5).

Part of their success laid in the modular building approach they adopted, which meant that each of the 32 individual modules were sent up from Earth in either single-use rockets or NASA's Space Shuttle (NASA 2007) (see Figure 3.6). Once in position, each module was attached to the ISS by astronauts during spacewalks. A series of robotic arms and special purpose tools were also developed to aid in the assembly process (NASA 2007). Today, the completed ISS stretches 243 feet (74 meters) by 361 feet (110 meters) – bigger than a football field.

While space agencies ran the construction of the ISS, the ongoing supply and transport of astronauts to and from Earth are currently being handled by private companies. In 2016, NASA awarded contracts to SpaceX, Sierra Nevada Corporation, and Orbital ATK to bring cargo to the ISS through 2024. SpaceX made its first transport of astronauts to the ISS in November

Figure 3.5: International Space Station (source: NASA/Roscosmos).

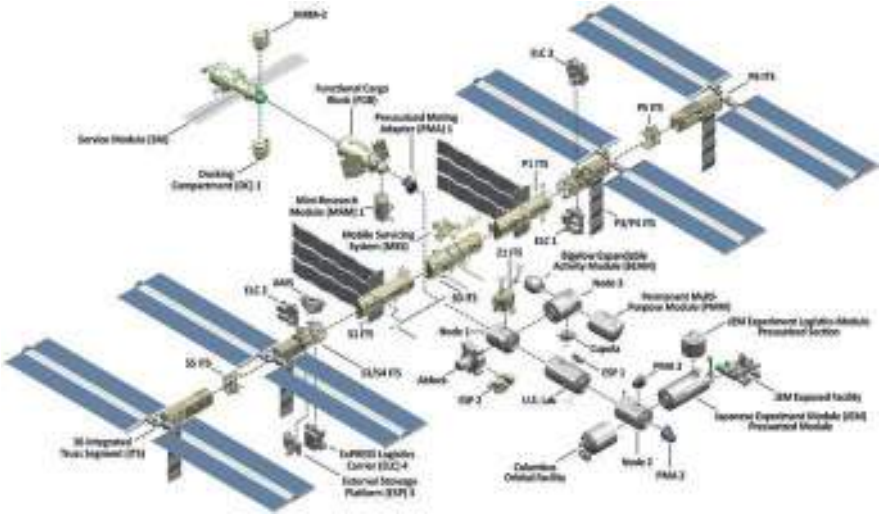

Figure 3.6: Components of the International Space Station (source: NASA).

2020, breaking a dry spell whereby the U.S. had not sent any humans into space from its own soil since the Space Shuttle program was retired in 2011.

Electricity for the ISS comes from solar power. Arrays measuring 27,000 square feet (2,500 square meters) stretch far from the main habitation modules of the station and generate enough electricity to power ten homes at approximately 110 Kw (NASA 2007). This is the largest power system designed in space and is extremely complex, consisting of multiple systems, backups, batteries, and untold numbers of cords, cables, and switches (Gietl et al. 2000).

The interior space of the ISS is cramped, but personal space is available for each astronaut, including some degree of soundproofing for privacy (Jones 2016). LED lights simulate a circadian cycle for the ISS residents, necessary because otherwise the 16 sunrises and 16 sunsets they see per day could be overwhelming (Weitering 2017; NASA 2017). Mental health is an ongoing issue for the ISS, and some internal audits have raised concerns about long-term health risks of ISS residency, with similar warnings for proposed long-distance missions like a Mars journey (NASA 2015). Minor things like effective thermal controls to regulate body temperature (NASA 2001) and having access to large windows to be able to see Earth have been shown to have a positive impact on the ISS crew's wellbeing (NASA 2015).

Recently, NASA hired the space company Axiom to build a new commercial module to be added to the ISS. In an interview with *The New York Times*, the company's president and chief executive, Michael T. Suffredini, a former NASA administrator, reflected on the extraordinary human achievement of starting to settle low-Earth orbit: "In any government exploration in the history of mankind, you send out a few people that are government funded to go do a relatively risky thing, just to see what's there…" Mr. Suffredini then went on to explain "we need to get to the pioneering stage, which is what we're really doing" (Chang 2020, p. D3).

Architecture and Urban Planning on the Moon

More than 50 years after sending people to the surface of the Moon, the U.S. is making plans to return and establish a permanent settlement to serve as a base for further space exploration (NASA 2020). NASA's Plan for Sustained Lunar Exploration and Development, nicknamed Artemis, would establish an outpost on the surface of the Moon. While the immediate planning is for structures to host up to only four astronauts for just a few months, NASA intends for this outpost to grow as the Moon becomes a launchpad for exploring Mars and beyond. NASA explains it this way: "Over the next decade, the Artemis program will lay the foundation for a sustained long-term presence on the lunar surface and use the Moon to validate deep space systems and operations before embarking on the much farther voyage to Mars" (NASA 2020, p. 2).

The current plan is for an outpost to be sited at the lunar South Pole, to be called the Artemis Base Camp, directly following a scheduled 2024 landing (NASA 2020, p. 4) (see Figure 3.7).

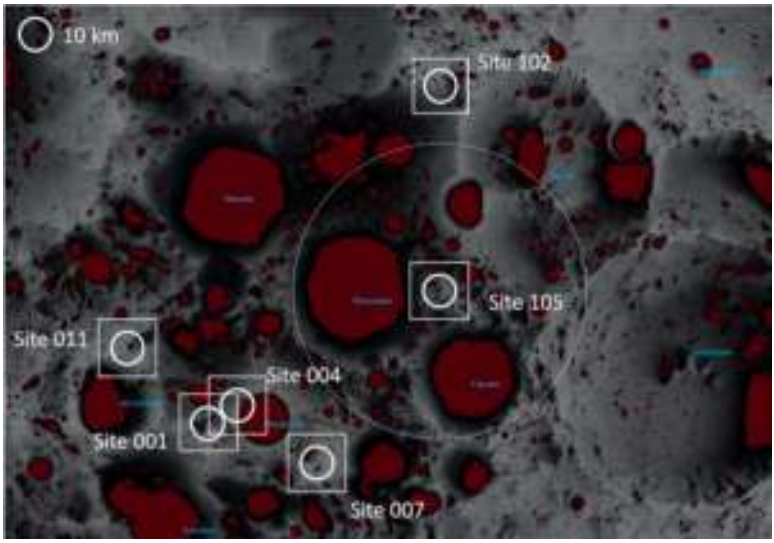

Figure 3.7: NASA's Artemis plan for a permanent settlement on the Moon is considering several possible sites in the South Pole region, particularly those in shadowed regions (source: NASA Artemis Plan 2020).

The NASA report envisions "supporting infrastructure added over time such as communications, power, radiation shielding, a landing pad, waste disposal, and storage planning" (NASA 2020, p. 9), enough to eventually accommodate much larger populations. For transportation, NASA proposes reliance on individually operated lunar terrain vehicles (LTV), though more elaborate automated transit systems may come later.

Regarding architecture, NASA has two elements in mind: 1) foundation surface habitat and 2) habitable mobility platform. Figure 3.8 illustrates how early landings allow for the development of a simple foundation surface habitat that sits permanently on the surface and acts as a base of operations, while the habitable mobility platform allows astronauts to explore great distances away from that Artemis Base Camp, providing mobile accommodations for eating, sleeping, and life support.

Technologies Needed for Off-World Living

Two decades of humans living on the ISS is itself pretty convincing evidence that we have mastered the basic technologies to live in space (albeit for limited durations). Between manufacturing techniques, methods of protecting people, recycling systems, agriculture, and heat and energy, we have the science

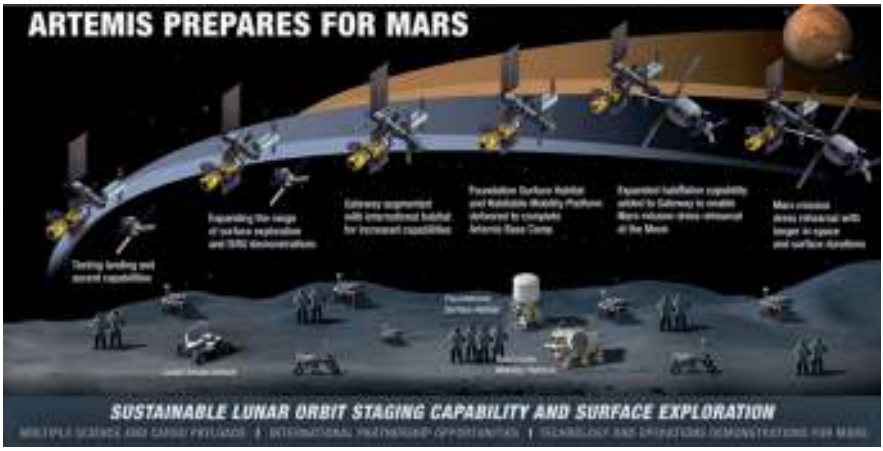

Figure 3.8: Rendering of Artemis base camps, illustrating how the facility will be staged to support future space exploration (source: NASA 2020).

and engineering acumen to become a true spacefaring people. These lessons have been learned through exploration and experimentation both on the ISS and through other missions, to the Moon, Mars, and elsewhere. It is worth noting that beyond low-Earth orbit, the most time humans have ever spent on the surface of a non-Earth celestial body is the Apollo 15 mission, where astronauts inhabited the Moon for a mere 12 days and 17 hours (Häuplik-Meusburger and Bannova 2016, p. 196).

Building in space has demanded important innovations around 3D printing in microgravity and with limited energy and material sources. NASA's In Space Manufacturing (ISM) Project has the tagline "make it don't take it" and advances various programs to allow for long-duration space flights and future off-world settlements that are "Earth independent" for equipment and supplies (Litkenhous 2019; Prater et al. 2019). The ISS has proven much of this technology at a basic level in producing needed parts and using the Refabricator to recycle material on the ISS for new purposes (Litkenhous 2019).

Astronauts on the ISS are quite vulnerable as they whip around the Earth at 27600 km/h, first from radiation and second from space debris. Scientists have refined two major elements of radiation protection over the years: polyethylene and Kevlar, both widely used and shown to be effective at shielding the astronauts from some levels of radiation, although long-term effects are still unknown (Narici et al. 2017; Pugliese et al. 2010). Space debris has been blocked on the ISS through the Whipple Shield design, essentially a front bumper on the space station – see Figure 3.9 (Cha et al. 2020). This kind of technology can be transferrable to spaceship design for travelling to Mars and

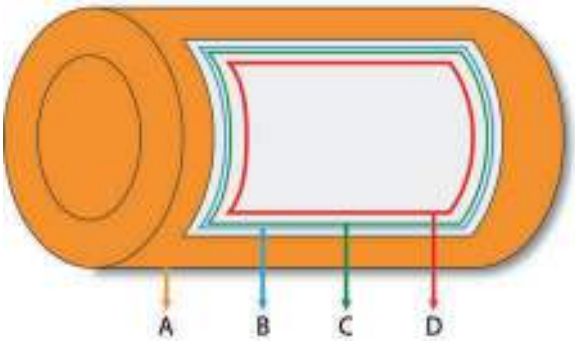

Figure 3.9: Whipple shield diagram. A = front bumper, B = insulation, C = middle bumper, and D = primary structure (source: Aliya Magnuson, adapted from Cha et al. 2020).

for architecture on Mars, to protect structures from potential debris, though modifications would be needed to match atmospheric and pressure conditions on Mars.

What is still unknown technologically speaking is whether these protective advances will be sufficient to keep a sizable human population on Mars safe for years and decades. The recent experiment on the ISS of keeping two men in space for a year each revealed vast strains on their health during that period and projected long-term health issues for both (Zwart et al. 2014; Turroni et al. 2020). The unique radioactivity, atmospheric pressure, gravity, dietary, and unknown debris threats on Mars means that until we land humans and begin to test these protective technologies in situ, we won't be able to confidently protect people.

Given the unique atmosphere, air pressure, and lack of breathable air or abundant sources of liquid water, settling Mars requires know-how around air and water recycling systems. Much of that innovation has advanced on the ISS due to its own limited supplies of these precious resources. Oxygen generator systems create oxygen using electrolysis, which splits water using electricity, providing ISS astronauts with air to breathe. Closed-loop water systems likewise take waste water and create drinkable water for ISS astronauts through purifiers (Engelhaupt 2014). See Figure 3.10 for a detailed depiction of how the ISS recycles air and water.

The ISS closed-loop system is in fact only partially closed; it suffers from substantial seepage that requires regular external resupply (Pickett et al. 2020). New improvements in technology and engineering would be needed in a future Martian colony if in situ generation of water and oxygen is impossible.

While ISS astronauts still get their food from Earth, they and scientists on Earth have been experimenting with off-world agriculture for decades. The ISS itself has had success with growing lettuce and zinnia (Massa et al. 2017).

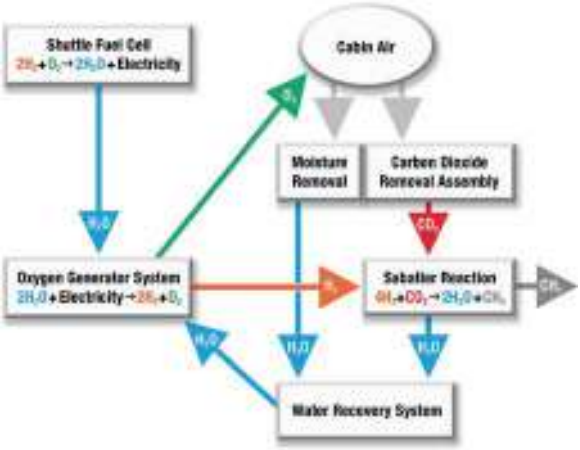

Figure 3.10: A "closed loop" on the International Space Station (source: NASA).

For heat and power, solar panels described earlier in the chapter keep astronauts on the ISS warm and comfortable. Nuclear energy has been widely used on other space missions for decades (Campbell et al. 2013). Small-scale reactors are another proven technology that can operate easily on the surface of a planet like Mars to provide full energy and heating needs (Campbell et al. 2013).

Numerous esteemed scientists and scholars have rejected the near-term feasibility of a human landing and settlement on Mars, raising concerns around some of the technical limitations already mentioned, as well as other serious engineering difficulties such a mission would entail (Rapp 2007; Szocik 2019). Yet the technological innovations that brought us to and sustained life in low-Earth orbit for more than 20 years are astounding by any measure, and they have given us the prototypes that could make a settlement on Mars possible.

By making the assumption that we *can* get to Mars and survive there, the question driving this book is: when we do get there, how should we build cities?

Rough Timetable for Martian Settlement

This chapter has shown that we have learned much in seven decades of space exploration – enough to get to Mars and almost enough to settle there. Advances in just a few key areas of energy, life support systems, manufacturing, recycling, health protection, and agriculture, some of which could probably occur post-arrival, are all we might need to settle Mars. A concerted effort to make the trip and resources to back it up can get us over some of the

technological hurdles. The following five chapters go into much greater detail around the science, engineering, and planning challenges in building a Martian settlement. These chapters draw on a variety of Earth-based and space-based analogs to develop a series of principles to guide the city design process, with the massive caveat that not all technologies are well tested and proven quite yet.

Humans have not always been the most patient species; we sometimes leap before we ought to. In space exploration and adventure, this is no less true. Numerous timetables have been developed for potential Martian colonization that rely on the aggressiveness that has motivated explorers for millennia and that pushed NASA to land the first man on the Moon. Somewhat artificial, these schedules can push us to advance science to make such a mission possible, even if it might just not be today.

According to NASA's Artemis program described earlier, the Moon would be a launchpad for reaching Mars in the 2030s (NASA 2020). Perhaps such a permanent base may one day facilitate future interstellar travel, as was imagined in Stanley Kubrick's film *2001: A Space Odyssey* (Kopping 2019). The privately owned company SpaceX, led by Elon Musk, is predicting the beginning of Martian settlement in 2025, while the United Arab Emirates intends to build a city of 600,000 on Mars by 2117 (Brown 2019). Noted astrobiologist Lewis Dartnell predicts that people will begin settling Mars before 2040, but substantial cities won't be built for 50 to 100 more years (Brown 2019). Science journalist Stephen Petranek predicted in his 2015 book that people would be living on Mars within 20 years, by 2035.

If a Martian settlement happens in the 2030s, it will likely not be the only off-world activity by that time. Plans to expand and eventually replace the ISS are expected to accelerate in the coming decades, allowing it to provide more room for human habitation and serve as a supply station for more distant missions (Paniagua et al. 2008). Futurists have speculated about near-term opportunities in mining asteroids and possibly settling them during periods of resource extraction (Shaer 2016; Krolikowski and Elvis 2019). As with asteroids, the Moon may be an attractive location for mining, particularly Thorium, Smarium, and Nickel (Campbell et al. 2013, p. 193–200).

Keep on Spacefaring!

With costs estimated to exceed $100 billion just to get to Mars, there are still a multitude of financial and logistical barriers to colonization (Rapp 2007, p. v).

In 2017, NASA chartered the Mars Exploration Program Analysis Group (MEPAG), an assembly of some of the most highly regarded space scientists in the U.S. The group articulated four overarching goals to guide NASA's Mars missions:

1. Determine if Mars ever supported life
2. Understand the processes and history of climate on Mars
3. Understand the origin and evolution of Mars as a geological system
4. Prepare for human exploration

The first three are all important, but it is the fourth that underpins all of the work in this book. The group further elaborated that their goal here was to "obtain knowledge of Mars sufficient to design and implement sustained human presence at the Martian surface with acceptable cost, risk, and performance" (Banfield et al. 2018). The goal of settling Mars is one of the pillars of this group's scientific aims, furthering human technological progress to allow for such a "sustained human presence" to occur. The lessons from seven decades of space exploration, combined with a genuine assessment of where we are technologically and where we need to get to, sets this goal up for NASA and while not guaranteed, becomes a realistic aim. Assuming this can happen – that humans can get to Mars and survive there – the remainder of this book serves as a roadmap for what just may come in that not-too-distant future.

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4

Designing Mars for Humans: The First Principle

When I tell people of my interest in urban planning on Mars, the most common response is laughter, then a bit of naysaying: "it can't be done", "too expensive", or "why would anyone want to live there?" Throughout the remainder of the book, I will address these and many other questions that might be swirling around in your own mind, nagging at you and making you feel incredulous. In this chapter, I address a problem that few envision: how do we build settlements for humans where they will thrive on an emotional and psychological level? So much of the concerns that I typically hear are rooted in the physical challenges of living on a planet without air to breathe and water to drink, with exceedingly high radiation exposure, low air pressure, and in a location 50 million miles from any other civilization.

Amazingly, there is a growing coterie of renowned scientists, engineers, and entrepreneurs who today are no longer bothered by those challenges and are preparing for human missions to the Red Planet. But the mental dimension remains a key stumbling block in those efforts. University of California, Davis social psychologist Albert A. Harrison considered the question of humans living on Mars or elsewhere in outer space and insisted that the key aim for planners ought to be that settlers enjoy "a lack of neuropsychiatric dysfunction, and the presence of high levels of personal adjustment, cordial interpersonal relations, and positive interactions with the physical and social environments" (Harrison 2010, p. 890). Studies have shown that in the U.S., the neighborhood you live in is largely correlated with your health and well-being (Pickett and Pearl 2001; Finch et al. 2010; Morenoff and Lynch 2004). We can likewise extrapolate that the physical environs that comprise Martian settlements will matter as well.

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J. B. Hollander, *The First City on Mars: An Urban Planner's Guide to Settling the Red Planet*, Springer Praxis Books, https://doi.org/10.1007/978-3-031-07528-5_4

A large body of evidence in environmental psychology, cognitive science, and neuroscience points to the role that the design and layout of settlements play in shaping our emotional and psychological states. I have personally been involved in this research and translating it to aid urban planners and designers (Hollander and Foster 2016; Sussman and Hollander 2021; Hollander and Sussman 2021). The key takeaway is that human evolved to seek out certain patterns, shapes, colors, smells, and sounds. The preference for curved lines over jagged lines is a trait believed to have evolved to protect us from predators and their sharp (jagged teeth), and that was conserved from species to species over millennia (Bertamini et al., 2015; Sussman and Hollander 2021; Vartanian, et al. 2013). To the extent that the design of homes, neighborhoods, schools, offices, parks, and other places consider those traits and give people what they unconsciously want, we can expect that people will be less anxious, will walk more, and will generally be happier. The evidence for this claim is not conclusive, but substantial, and can serve to guide Martian urban planning.

The principles to follow can be thought of as the menu for an urban plan, a schematic for the siting and form of structures, which ought to have strong attention to edges, shapes, patterns, narrative, and biophilia. The design of plazas, parks, streets, and pathways should be based on these principles, with adjustments due to local constraints and engineering considerations (as will be presented in Chapters 5, 6, 7, and 8).[1]

Edges Matter

Since 1756, Princeton University has anchored the small town of Princeton, New Jersey. The illustrious university's main campus occupies 350 acres of historic buildings and beautifully landscaped grounds. Nassau Street is the college's northern boundary, separating it from downtown Princeton. All hours of the day and night, this street is alive with student revelry, shoppers, and diners who frequent Nassau Street establishments and those in the roughly 350-acre business district to the north. A dream urban village for architects and planners, downtown Princeton has the right mix of pedestrian scale, buildings and uses, green space, and urban design elements that scholars like Ewing and Bartholomew (2013) call for in their bestselling urban design manual, *Pedestrian & Transit-oriented Design* (see Figures 4.1 and 4.2).

[1] The following sections derive from literature review research that I conducted with Ann Sussman for our 2015 book *Cognitive Architecture: Designing for How We Respond to the Built Environment* (2nd edition published in 2021) and with Veronica Foster for our 2016 journal article "Brain responses to architecture and planning: a preliminary neuro-assessment of the pedestrian experience in Boston, Massachusetts."

Buildings close to the street, a variety of façade types and materials, attention to the characteristics of the street wall; downtown Princeton has it all.

Designers today, like Ken Greenberg, lament that this type of urban development, grown organically over centuries, is so hard to recreate (Radiant City 2006). Noted urban critic James Howard Kunstler (1994, 1998) has written extensively on this point: the characteristics of a place like downtown Princeton are to be emulated, but doing so is rare and difficult.

Palmer Square is the epitome of what makes downtown Princeton so popular with architects as well as shoppers, visitors, and Princeton students. Note the variation in the street wall, the crafting of the public realm, and the design of the pedestrian circulation system (Figures 4.1 and 4.2). Straight out of Ewing and Bartholomew's classic manual mentioned earlier. Of course Palmer Square's architect, Thomas Stapleton, designed the complex about 80 years prior to the manual.

What's happening here? Without the extensive documentation of the "best" design strategies, how did Mr. Stapleton know what to do? How did his design generate a destination that endures as a high quality urban space so many years later? Part of the answer lies inside all of us: our brain.

Whether Stapleton knew it or not, his design for Palmer Square reflects a keen appreciation of thigmotaxis. It is the notion that we orient ourselves within space according to strictly defined rules embedded in our brains. We do this subconsciously, routinely, and automatically. Walking down Palmer Square's Hullfish Street, we hug the street wall, our eyes absorb our

Figure 4.1: With a focus on pedestrian-orientation, the designers of Palmer Square (Princeton, New Jersey, USA) made it a comfortable place for people to walk and socialize. (source: photograph by Justin Hollander).

Figure 4.2: With stores close to the street, an active streetscape, and varied architecture, this street in Palmer Square is very inviting to pedestrians (source: photograph by Justin Hollander).

surroundings, and we feel a certain level of peace and security – all because of how the place is designed.

In my book with Ann Sussman (2015), we argued that human preference for edges (wall-hugging or thigmotaxis) is part of our evolutionary heritage. Wall-hugging here means the unconscious impulse to maneuver around ones' environment with close, tactile connections to walls or edges. "Thigmotaxis" is a Greek word that means touch and shape and has been widely used as a technical term for wall-hugging by natural scientists. Many species exhibit this thigmotaxic behavior, from paramecium (Jennings, 1897), to earthworms, (Doolittle 1972), frogs (Bilbo, et al. 2000), and snakes (Greene, et al. 2001). Most research on thigmotaxis has focused on non-human animals, but recent evidence suggests that humans prefer edges as well (Kallai et al., 2007) (see Figure 4.3). In this study, Kallai found the presence of the thigmotaxis trait in humans based on studies they conducted of human movement along corridors.

While edges are generally preferred, not all edges are created equal. Ewing et al. (2016) sought to quantify the best streetscapes by counting pedestrian activity and found that the busiest places also had active uses, street furniture, and permeable edges (windows on the ground floor). Ann Sussman and I argue that there are three features that influence the quality of an urban edge, focused

Figure 4.3: A line of cars on one side and a park with benches, trees, and a light fence on the other create substantial edge conditions, making Palmer Square a comfortable place for people to walk, sit, and socialize (source: photograph by Justin Hollander).

largely around facades: (a) permeable walls (doors, windows, arches); (b) varied materials (changing every 30′–50′); and (c) overhanging features (awnings).

Patterns Matter

In 1960, Kevin Lynch coined the term "imageability," which has persisted in urban design circles ever since, as evidenced by the fact that it is highlighted by Ewing and Bartholomew (2013) as their first of eight urban design qualities. As they put it, "a place has high imageability when specific physical elements and their arrangement capture attention, evoke feelings, and create a lasting impression" (p. 11). They go on to explain that imageability "plays to the innate human ability to see and remember patterns" (p. 11). They conclude by stating that "vernacular architecture" is an important contributor to imageability (p. 12).

But imageability is more than just about evoking feelings and remembering patterns; it is part of a deeper quality of the built environment that is ingrained in our minds. Our minds do indeed seek out patterns in the environments we find ourselves in, but the pattern goes beyond a vague arrangement of physical elements. Scientists have unequivocally shown that two important patterns make a difference in how we experience our environments: (1) the Golden Rectangle, and (2) faces.

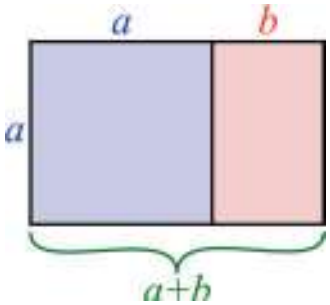

Figure 4.4: The Golden Rectangle (source: Ahecht (Original); Pbroks13 (Derivative work) / CC0 1.0).

Allen Jacob's work is heavily cited in Ewing and Bartholomew's volume as well as throughout the design and planning literature. His seminal book *Great Streets* (1993) is a classic in the design of streets and their environs. Based on anecdotal evidence and years of practice, he writes that the proportion between a building's height and the width of a street should be at least 1:2. In 1509, Luca Pacioli published *Divina Proportione* introducing the idea of the Golden Rectangle, a pattern that since then has emerged as the preferred shape globally. Its dimensions are roughly 1:1.6, not too far off from Jacob's prescription (see Figures 4.4 and 4.5).

Pacioli picked up on something so much more powerful than any old shape. The Golden Rectangle has been shown by scientists to represent a shape unlike any other when seen through the lens of the human brain (Bejan 2009). It turns out that certain ratios and proportions in the built environment are better or worse, for a very good reason: when humans look out on our environment, we can scan horizontally faster than we can scan vertically. Bejan (2009) argues that a 1:1.6 dimension allows us to scan both directions in the same amount of time, improving our visual efficiency and performance (Sussman and Hollander 2021).

The other pattern that matters is one we stare at all the time: the human face. The unique arrangement of eyes, mouth, nose, ears, and hair really matters. Infants when first born recognize faces unlike any other shape. That same recognition persists as we grow and mature and is extended into the built environment. When we look around us, we seek out the patterns of faces. Scientists have found extensive evidence that looking at a face activates unique portions of our brains and affect us differently than looking elsewhere (Kandel 2012; McKone, et al. 2012; Kanwisher, et al. 1997). As with the power of imageability, looking at faces in buildings, in streetscapes, and on signs also evokes feelings and affects us.

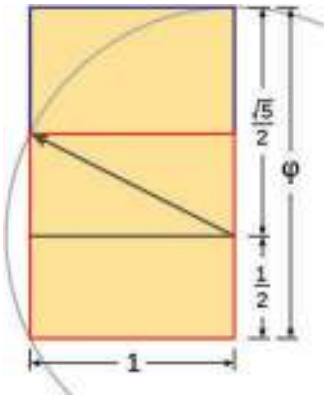

Figure 4.5: Calculations needed to generate the Golden Rectangle (source: Joel Holdsworth / Public Domain Mark 1.0).

Shapes Carry Weight

The two previous principles have established the role of wall-finding behavior and pattern recognition as central to understanding how the built environment affords us certain benefits and insights. These principles elucidate the very critical "why" of select urban design principles widely accepted as fact by both practitioners and scholars. By understanding why, the designer is freed from the obscure rules regarding how to create public space or generate safe and comfortable places. With these principles, the designer can go farther and do better.

I now turn to the third principle: shapes carry weight. The importance of bilateral symmetry and hierarchy are fully ingrained in classical architecture and urban design, beginning with Vitrivius and continuing with the great Renaissance architect Palladio. John Summerson (1963) wrote "...the aim of Classical architecture has always been to achieve a demonstrable harmony of parts. Such harmony has been felt to reside in the buildings of antiquity and to be of a great extend 'built in' to the principal antique elements – especially to the 'five orders'" (p. 8). Here Summerson is referring to the five column forms, which serve as the literal building blocks for Classical architecture: Tuscan, Doric, Ionic, Corinthian, and Composite (see Figure 4.6 for a more elaborate version of the five orders created during the Renaissance, when a sixth order was introduced).

Moughtin and Mertens (2003) wrote that these principles have become mainstream and modernized by expanding their symmetry to encompass balance and rhythm. Ewing and Bartholomew have embraced this turn in

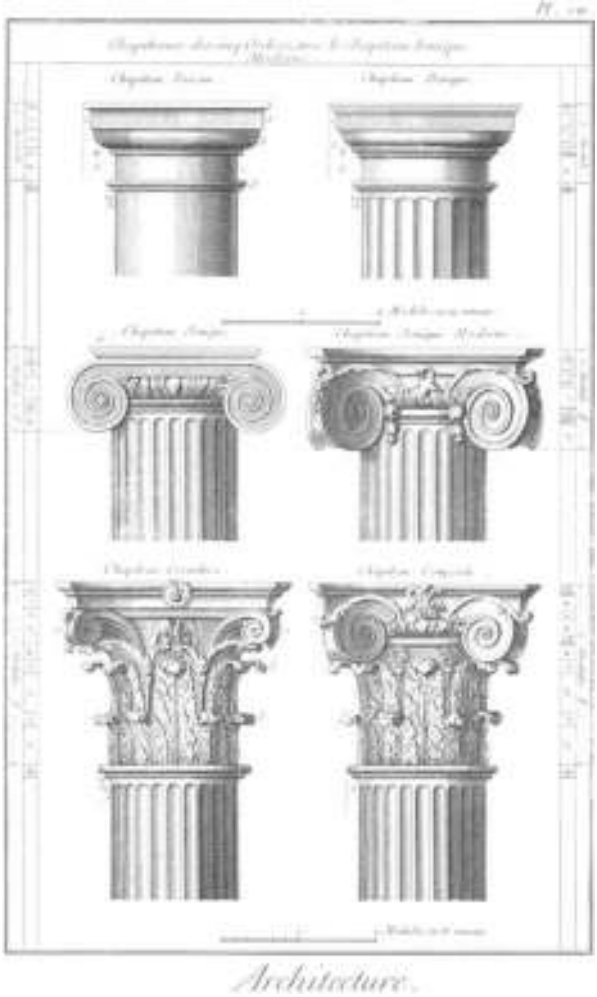

Figure 4.6: Engraving displaying the six types of columns in classical architecture (source: University of Chicago, converted to PNG and optimised by user:stw / PD-US).

interpreting symmetry, accepting a broader definition for it than left-right correspondence and bilateral mirror imagery, and calling instead for *coherence* and *legibility* in their eight urban design qualities.

For Ewing and Bartholomew, as for other contemporary designers, the strict rules of bilateral symmetry are of little use in creating great spaces. Instead, coherence provides a certain level of "consistency and complementarity in the scale, character, and arrangement of buildings, landscaping, street furniture, paving materials, and other physical elements" (p. 17). Legibility means that the physical elements of an urban space serve as reference points

for the occupant to help them feel oriented. Both of these urban design qualities touch on symmetry and hierarchy.

The Classicalists had in right: strict bilateral symmetry does put people at ease more readily than other forms and types of symmetry. The same findings are true for hierarchy: cognitive scientists have demonstrated a perceptual preference for visual forms that have a clearly defined top, middle, and bottom. The urban design quality of legibility comes closest to this in calling for demarcations between different elements of the built environment. Kevin Lynch's (1960) paths, edges, districts, and nodes persist in contemporary practice as the central organizing system for city design. What Lynch insists is that each element must be distinct and defined physically from the others. – for example, that paths and nodes ought not collide awkwardly, but rather that the designers should draw clear lines between each through the prodigious use of greenery, hardscaping, and signage.

The science is the same (in slightly different words) for hierarchy. By creating a visual order as rigid as the Classicalists' five orders, a present-day (or future) designer can tap into a brain-wired notion of hierarchy that creates comfort and security for the user of the space.

Storytelling is Key

For thousands of years, philosophers the world over have viewed stories as a fundamental dimension of the human experience, and today, neuroscience is showing that they were right (Young and Saver 2001). Without stories, scientists are arguing, we have no way to make sense of the world around us. Stories take otherwise senseless strings of words and sentences and organize them in a way that we remember. The same holds true for the built environment. Places that tell a coherent tale – that have a discernable beginning, middle, and end, that show plot and characters – are places that we can connect with on an unconscious, emotional level (Sussman and Hollander 2021).

Consider the top tourist attractions in the world, including the Grand Bazaar, Istanbul (91,250,000 annual visitors), the Zócalo, Mexico City (85,000,000), and Times Square, New York City (50,000,000); these are places rich in history and narrative (The World's Most-Visited Tourist Attractions 2014). Even fantasy-themed places like Disney World Orlando and Tokyo Disneyland get 18,588,000 and 17,214,000 annual visitors, respectively (The World's Most-visited Tourist Attractions 2014). It is not some kind of perfect, authentic experience that our minds need: we just need *that story*.

Whether it is a fairytale castle or a World War II battle site, people all over Earth are drawn to places that are full of stories. The word "history" itself connotes this fact: we care about the narratives or the "stories" of what happened in the past. This is all very good news in approaching the design of cities on Mars. Even without a past of human settlement, places on Mars can reference coherent stories that occupants may already be familiar with or may all learn together.

Biophilia Counts

From the Latin, *bio* (life) and *philia* (love), "biophilia" speaks to the innate connection that humans have to nature. Noted biologist E.O. Wilson wrote in 1984 that humans have a "tendency to focus on life and lifelike processes" and they experience a strong "urge to affiliate with other forms of life…" (Wilson 1984, p. 1). People innately "prefer open savanna-like terrain with scattered trees and copses, and they want to be near a body of water" (Kellert and Wilson 1993, p. 23).

Extensive research has demonstrated the psychological and physical health benefits for people when put in close connection with natural Earth environments or reproductions thereof. Painted nature murals in a waiting room made dental patients less nervous (Heerwagen 1990). After gallbladder surgery, patients with views of trees "had shorter hospital stays and suffered fewer minor post-surgical complications" than those who looked out of their window at a brick wall (Ulrich 2002). A systematic review of 25 studies concluded that exposure to natural environments broadly offered benefits to wellbeing (Bowler, et al. 2010). Most studies conclude that the impact of nature on humans is important and measurable (McMahan and Estes 2015), where the greatest dimensions appear to be around natural light, water elements, plants, and images of natural scenes (Gillis and Gatersleben 2015).

Kellert (2012) worried about much of the current built environment humans find themselves in on this planet, which leads to "sensory deprivation, where monotony, artificiality and the widespread dulling of the human senses are the norm rather than the exception" (Kellert 2012, p. 161). Kellert and others (Beatley 2017; Newman et al. 2017) advanced a campaign in architecture and planning for greater emphasis on biophilic design concepts, and in particular environmental features (plants, water, and sunlight), natural shapes and forms (botanical/animal motifs, shells, and spiral forms), natural processes and patterns (sensory variability), light and space (natural light), place-based relationships (making connections to places), and evolved human

relationships to nature (prospect and refuge, order, and complexity) (Kellert 2012; Sussman and Hollander 2021).

Central to the biophilic design premise is that humans evolved on the African savanna, and we retain a love and longing deep in our DNA for the forms and shapes and patterns of that environment. For Mars, which looks quite different from the savanna landscape, the biophilic imperative is to construct reproductions of Earth-like environments to such a degree that people can live millions of miles from home and, at least on an unconscious level, not really miss it.

Conclusion

Whether designing a public garden or urban plaza, this chapter offers a starting point for approaching the task. Distilling the state-of-the-art in urban planning and design practice is, in many respects, one of the aims of this book: once distilled, the challenge becomes applying that knowledge to inform planning for Mars. In this chapter, I have shown how humans have evolved to seek out certain patterns, shapes, and sights, which then are used as the basis for physical designs. While the emotional needs of some city occupants might be deemphasized over financial, military, or political considerations, we cannot take such a chance for the first generation of Martians. It is imperative that these cognitive architecture principles guide the planning strategies for Martian settlement, and that we create places where people will be happy, not just alive.

These cognitive architecture principles are distinct from the conventional urban planning standards one might find in a textbook or reference work. They are meta-level – they do not lend themselves easily to a precise width of a street or style of signage. Instead, for guidance on those questions, we must turn to those urban planning "best practices" that have developed over the years through trial and error through the art of city planning. Chapters 5-8 will report on those best practices, with a particularly close eye on our collective experience planning and designing places in harsh climates – those places on Earth that most resemble Martian landscapes.

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5

Transportation Dimensions

The design of human settlements is inextricably linked with transportation, with respect to both internal circulation and connection with other settlements. The most obvious example is the typical water port city on Earth, whether it be Boston, Rome, or Hong Kong. Deep harbors and easy access to waterborne transportation help explain the location of most cities globally. Other considerations also drive city location – notably access to other transportation networks (rails, canals, airports, or spaceports). Internal transportation matters greatly in considering the design and layout of a new city and, equally important, how that internal circulation system relates to an external network.

For this and the next three chapters, the various dimensions of urban planning on Mars derive from a comprehensive literature search I conducted with the help of many of my students at Tufts University. We sought out sources not only in urban planning, but also in the sciences and engineering disciplines. We also conducted searches for research that specifically examined these considerations relative to Mars and to challenging climates on Earth. By drawing on peer-reviewed scholarship, scientific reports, and published professional best practices, these chapters offer a holistic picture of what an urban planner for Mars needs to know about building, land use, transportation, and other infrastructure.

In this chapter, I introduce the state-of-the-art ideas and best practices in both internal and external urban transportation, all with an eye towards Mars. The chapter concludes with several key transportation design principles that will then be adopted in the plan for the first city on Mars (Aleph) presented in Chapter 10.

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J. B. Hollander, *The First City on Mars: An Urban Planner's Guide to Settling the Red Planet*,
Springer Praxis Books, https://doi.org/10.1007/978-3-031-07528-5_5

Noted entrepreneur and innovator Elon Musk found himself frustrated with the incessant traffic in his part-time hometown of Los Angeles, California. A metropolitan area of 10 million residents (US Census Bureau 2017) with only a nascent fixed rail public transit system, L.A. has more than half as many cars as people and the city's traffic congestion is infamous (Newton 2010). An impressive fleet of 2,308 busses (Metro.net 2018) traverse the same clogged roadways as cars, with the result that travelling even small distances can take hours. In 2016, Musk founded the Boring Company to begin boring a network of tunnels under L.A., where he would run a novel, private mass transit system to drastically decrease travel times around the metropolitan area. In late 2018, Musk announced that the first mile of tunnel had been bored, and he drove one of his Tesla electric vehicles from the SpaceX headquarters to a parking lot in Hawthorne, CA at a speed of 35 miles per hour (Blanco 2018).

Could a network of underground roads and subways be the answer to getting people around on Mars? Perhaps. The Martian climate is quite harsh: extreme cold, persistent dust accumulation, and exposure to high levels of radiation are all conditions any transportation engineer would fear when it comes to maintenance. Surely it is possible to build the equivalent of highways, bridges, and train tracks to traverse the Martian surface, but how long would that infrastructure last? Could it be cared for or repaired when needed?

Here is where boring makes sense: go underground! Under the surface, temperature extremes are modulated, there is no dust accumulation, and radiation exposure drops to a safe level for humans (Broere 2015) (see Figure 5.1). Boring tunnels on Earth is expensive and difficult. Musk is estimating an average cost of $10 million per mile for his L.A. project (Blanco 2018). This cost is actually a relatively affordable figure, as the Boring Company's website reports that tunnel boring can typically reach $1 billion per mile. Several major subway systems extensions planned in the United States have projected costs at nearly $1 billion per mile (Bliss 2018). Boring tunnels under the Martian surface will not be easy or cheap, that is certain. The likelihood of tectonic movements like we have on Earth could be an additional challenge to underground transportation infrastructure, though historically, shifting tectonics have rarely wreaked much havoc on underground roads or rails on Earth – the exception being the earthquake that tragically hit Kobe, Japan in 1995 and resulted in the first complete collapse of a reinforced concrete underground structure (Parra-Montesinos, et al. 2006, 113).

Lessons from Kobe suggest that increased ductility is important for structural members in underground construction, and extra attention should be paid to soil conditions (Parra-Montesinos, et al. 2006). Aside from Kobe, civil engineers broadly agree on the safety of underground structures, but costs and

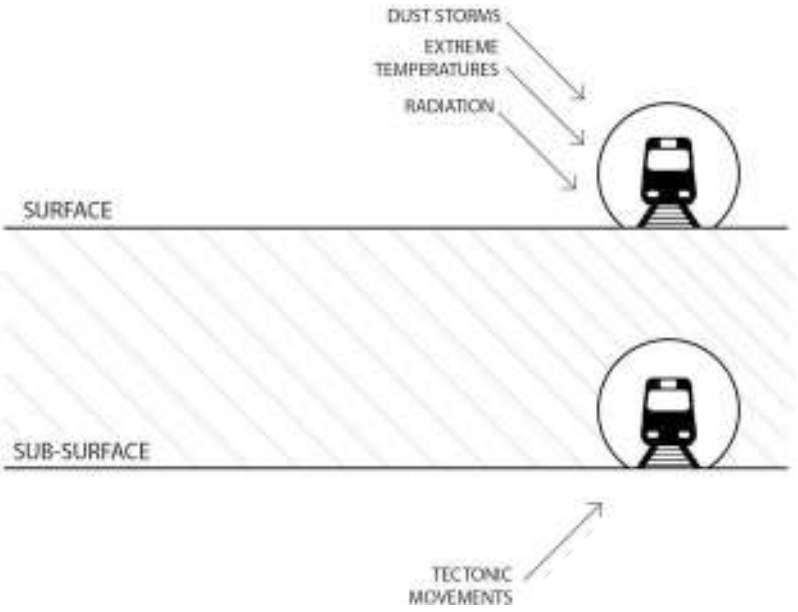

Figure 5.1: Risk exposure of surface and sub-surface tunnels (source: Berk Diker).

risks in the construction process remain obstacles. To reduce some of these risks and reduce costs, inspiration from science fiction is useful. Kim Stanley Robinson (1992) suggests in *Red Mars* that autonomous construction vehicles can do much of the expensive and dangerous work of digging, clearing, and building.[1] If the engineering and cost and safety hurdles of boring tunnels can be overcome, an underground transportation network may be the most efficient and effective answer for the City of Aleph.

Underground Transportation and Mass Transit

Within those tunnels, there are several options for how people would move about: 1) by some form of mass transit, 2) by individual or small groups of motorized, operated vehicles (automobiles), or 3) by foot or other human-powered vehicles, like bicycles.

The first generation of mass transit vehicles were stage coaches, which appeared in England in 1610. Since then, cities have constantly struggled with how to manage the flow of people within a city, how to referee the

[1] Serious non-fiction research has also speculated about the capabilities of robots to perform large-scale construction projects on Mars (Kading and Straub 2015; Boston 1996).

competition among different modes of transport, and how to protect the least advantaged (or slowest) travelers (Lay 1992). Urban planning on Mars will be no different. There are some lessons from Earth that are particularly useful.

Individual or small groups of operated motorized vehicles provide immense flexibility and individual liberty, yet when not managed well can generate immense congestion of the sort that many have witnessed in L.A. The automobile has profoundly shaped urban history, and as such has been harshly maligned by critics (Bruegmann 2006; Beauregard 2006; Kunstler 1994), but also feted in films like the *Fast and the Furious* and *Gone in 60 Seconds*, and in broader popular culture with the famed Batmobile, the subculture of street racing, and the environmentally minded movement towards electric cars (Graham-Rowe et al. 2012). In approaching a design for Aleph City, these lessons have to be considered and weighed against alternative means of transport.

What are the potential benefits and liabilities around giving primacy to a mass transit system? Thewes, et al. (2012) measured the surface area required for cars versus mass transit and concluded that a car-based transportation network requires between 30 and 90 times more space than mass transit. They also concluded in their research that mass transit results in faster travel times, lower energy consumption, and reduced noise pollution (Thewes, et al. 2012). Other scientists and engineers have studied mass transit systems and widely view them as a preferable foundation for a new city over a car network (Litman 2018; Spieler 2018; Glazebrook and Newman 2018; New York City Department of City Planning 2008). Spieler (2018) points to the New York City subway system as an archetype with its 232 miles of tracks, redundancy (three to four tracks for every subway line), and its ridiculous density: almost 150 trains pass through Lower Manhattan every hour (p. 51).

Pearson, et al. (2010) proposed a network of electric, aboveground improved roadways and railroads to connect settlements on the Moon. They emphasize the importance of considering *rolling resistance* when designing a transportation network – how much resistance a travelling vehicle's wheels will face as they traverse the lunar surface. Rolling resistance is measured as a coefficient, where 0.01 represents the weight of 0.01 pounds needed to pull one pound of weight. A rover driving on unimproved lunar regolith would experience a very poor rolling resistance coefficient of 0.12, requiring much more energy than what a typical car with tires faces driving on improved roadway on Earth (0.015) or metal wheels on metal tracks that might be seen on a typical railroad (0.005) (Pearson, et al. 2010). As such, Pearson, et al. (2010) recommend improved lunar roadways and the laying of metal tracks for trains.

Walking has been widely linked to biking in contemporary transportation practice, so I will address them together. These non-motorized modes of transportation can be very effective for short distances: think Ancient Rome or Historic Philadelphia (Pennsylvania, U.S.), both quite small cities and easily traversed by foot. But few modern cities can afford to be so concentrated and geographically small, with the range of uses, utilities, safety, and other considerations that today's urbanites expect. On Mars, it is hard to imagine cities small enough that people could just walk and bike around them. Maybe early cities could be that small, but the plans presented herein will offer an opportunity for long-term growth where additional transport options are needed beyond foot and bike.

As a secondary system for getting around, a comprehensive network of pedestrian and bicycle paths is seen on Earth as a requirement by many prominent scholars and government bodies (Pardo 2010; European Commission 2007; Pucher and Buehler 2012). Such a bike/ped network has a multitude of measurable benefits, first of which is redundancy. In the event that the primary mass transit system fails, people will still be able to travel. Another benefit is exercise: walking and biking have been shown on Earth to be an important means by which people burn calories, build muscle, and keep fit (Hörder, Skoog, and Franden 2013; Morris and Hardman 1997; Ogilvie, et al. 2007).

There are significant differences between gravity on Earth and Mars, which has implications for both walking and biking. The mechanical process of walking on Mars is roughly half of what it takes to walk on Earth and therefore consumes less energy (Cavagna, et al. 1998). But the low-gravity Martian environment also means that walking tends to be slower, with one team of scientists arguing that the optimal walking speed on Mars is 3.4 km/hr compared to 5.5 km/hr on Earth (Cavagna, et al. 1998). Walking is a process where our legs are exchanging potential and kinetic energy, like in a pendulum, and the problem is that low gravity disturbs this relationship (Pavei, et al. 2015).

There has been a notable consensus in kinesiology and biomechanics that skipping instead of walking is likely the best way to navigate Mars (Pavei, et al. 2015; Ackermann and van den Bogert 2012). Apollo astronauts traversed the low-gravity lunar surface by skipping. Because skipping is an "asymmetrical gait," it is easier to change directions than walking and is less "fatiguing and more economical" in low gravity (Pavei, et al. 2015, p. 99; Ackermann and van den Bogert 2012, p. 1298).

Many of these concerns could impact bike travel on Mars. With lower gravity, traction is reduced somewhere between 5-10%, interfering with

stable and safe control of bicycles (Niksirat, et al. 2020). However, roboticists and engineers have explored a variety of strategies to retrofit bikes with improved mechanical systems to overcome the traction issue, with one study concluding that biking in low-gravity environments could be safe (Wong and Kobayashi 2012).

Aboveground Aerial Tram

Aerial trams and gondolas have been a persistent feature of transportation systems on Earth for generations. They were identified by a NASA contractor in 1992 as the most preferable transportation system for hauling raw materials around a proposed Martian settlement, and more recently the idea was touted again by a team of space researchers (Pearson, et al. 2010). In their original analysis, Ayers, et al. (1992) considered various surface trains, elevated trains, and a magnetic levitation. They concluded that an aerial tram would be the simplest and easiest to build and maintain, and it would also be the lightest option on Mars (see Figure 5.2). The authors projected that an aerial tram system could transport 216 metric tons per day of raw materials (Ayers, et al. 1992, p. 6), a key component of any Martial settlement.

While the tram depicted in Figure 5.2 employs a bucket design for industrial uses, it could also be retrofitted to support human transportation needs. The tram has been around on Earth for so long because of its simplicity and ease of construction – builders need just two stations and "intermediate trestles for support" in between the stations (p. 6). However, concerns around radiation exposure, atmospheric conditions, and temperature fluctuations still make the underground option for human transport quite attractive if underground boring expenses can be overcome.

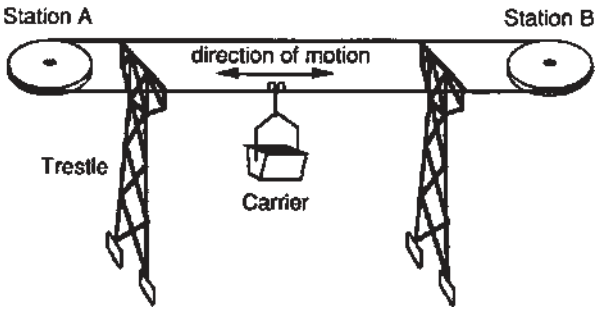

Figure 5.2: Proposal for an aerial tram on Mars (source: Kaplan, et al. 1992).

Bike and Pedestrian Transportation System Design

Regarding specifics of pedestrian transportation design, several scholars have studied optimal routes and path systems. Ciolek's (1978) work provides key guidance on the best way to lay out paths around objects, arguing for minimizing the route between the point of departure and point of destination whenever possible (see Figure 5.3). He also worries about people colliding into objects or other people and as such recommends safe gaps in laying out pedestrian pathways, with 30-60 cm for gaps between an obstacle and a person and more than 60 cm for a gap between two people (see Figure 5.4). Of particular note is that these gaps need to be higher in areas of poor illumination or large crowds. Lastly, Ciolek cautions against sharp turns or edges in pedestrian path design, recommending no turn that exceeds 30 degrees (see Figure 5.5).

Others have also studied walking paths, among the most famous being feted architect and urban planner Jan Gehl. His *Cities for People* (2010) book offers additional guidance and evidence to support Ciolek's work. Both scholars deride sudden and significant changes in elevation on walkways, arguing that people have a deep-seated preference against stairs or ramps. Likewise, Gehl, Ciolek, and others have long recommended that the route of pedestrian paths provide ample visual stimulation: whether aboveground at street level or belowground, humans seek out variation in edge activity every 30 feet or so – for example, changes in building material, storefront design, colors, or opacity (Sussman and Hollander 2021).

In addition to these considerations, the planning of these underground pedestrian paths should incorporate options for bicycle or other non-motorized transport in separated paths. Examples of successful bike and

Figure 5.3: Preferred walking path vs. existing path (source: Berk Diker).

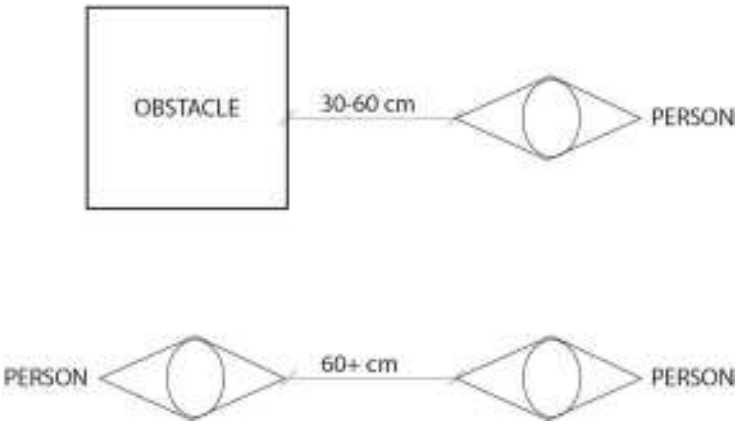

Figure 5.4: Preferred distance left between objects and people when walking (source: Berk Diker).

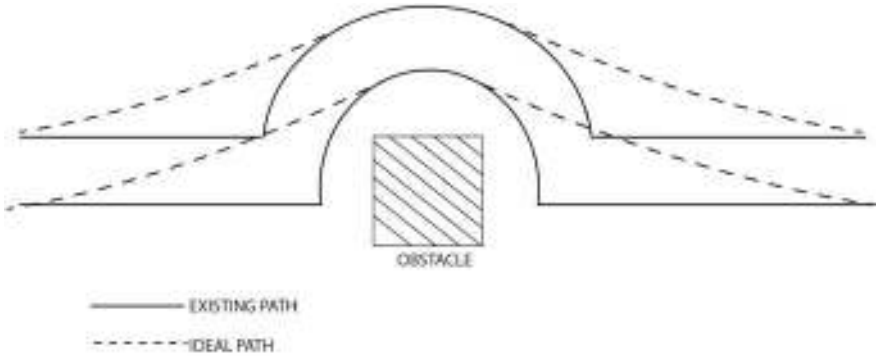

Figure 5.5: Optimal walking path around an obstacle (source: Berk Diker).

pedestrian infrastructure exist throughout the globe, with notable examples in Copenhagen, Denmark, and Melbourne, Australia (Gehl 2010).

In my own backyard, the Minuteman Bike Path stretches across four cities and towns in Greater Boston and has links to mass transit and major employment centers. The path is a converted rail bed and is 12 feet wide (minutemanbikeway.org 2019). It accommodates a range of non-motorized vehicles, walkers, and runners without physical separation. See an example of a separated bike/ped path in Figure 5.6.

These new, separated paths tend to be much beloved in their communities and have been cited by their planners as hard to pull off but significantly impactful (Bunnell 2002). Converting rail lines into trails that are separated

Figure 5.6: Photograph of the Paul Dudley White bike path on the Charles River Esplanade in Boston, Massachusetts, USA (source: Whoisjohngalt / CC BY-SA 4.0).

out from automobile routes, cars, and trucks, is an attractive way to enhance mobility options, but is challenging to accomplish and limited in scope. These separated paths represent a small minority of all roadways in most cities.

In the case of a new town design, the opportunity to physically separate bike/ped and automobiles routes might be viewed as attractive, but it is a rare approach. One exception is the plan in the downtown district of Tsukuba, Japan (Takahashi 1981). The city was built in the 1960s as a new academic and government research center for Japan, approximately 60 km from Tokyo. From the very beginning, Tsukuba planners envisioned a transportation network with vertically separated systems. The first level would be oriented towards automobiles (though providing space for bicycles and pedestrians), while there would be an above-grade, raised "overstreet" of parks and bike/ped paths (see Mayerovitch's [1973] treatise on this overstreet model).

The vertically segregated transport routes accomplished several key goals: they 1) reduced the potential harm to pedestrians and bicyclists from close contact with cars, 2) enhanced the speed with which these non-motorized users could circulate the city, avoiding the delays of stoplights and other road hazards, 3) provided a more economical means by which ordinarily underground infrastructure (like electrical, HVAC, communications, water, and sewer systems) could be installed in the overstreet system, and 4) expanded the availability of land for parks and open space (Mayerovitch 1973).

I had the opportunity to travel to Tsukuba in 2019 and see firsthand how the city has evolved since it was built five decades ago. The current city exhibits signs of new growth and development, yet the basic framework imposed at the city's early design stage to manage transport has held up very well. I was

impressed by how such forethought resulted in a pedestrian and bike experience unlike anyplace else I have been. Surely, these separated paths exist elsewhere, but Tsukuba's downtown district extends such separated paths across almost an entirely different city, elevated above the automotive traffic below (see Figures 5.7 and 5.8). Such prior planning allows a denizen of Tsukuba to travel by bike or foot through the entire downtown district without having to come in close contact with cars or trucks.

Figure 5.7: Pedestrian and bicycle path through the downtown district of Tsukuba, Japan (photograph by Justin Hollander).

Figure 5.8: View of lower roadway from pedestrian and bicycle path bridge in the downtown district of Tsukuba, Japan (photograph by Justin Hollander).

While physical separation is extremely attractive, it is only one of a number of design solutions that bike researchers have found can make a difference in encouraging the use of bicycles and safe outcomes, many of which are applicable on Mars. Chunli, et al. (2018) look at the big picture and recommend that bike network designers consider "cohesion" (connections with other modes and lack of gaps in network), safety (separation of motor vehicles and bikes), directness, and comfort/attractiveness. Other scholars have focused more on the details, calling for attention to intersections (where most accidents occur), adequate lighting, a smooth pavement material, and adequate bike parking at public transit stations and stops (Litman, et al. 2009). The lanes themselves should be at least 1.2 meters per lane wide or 4 meters wide for high traffic areas (Litman, et al. 2009, 16). These are all useful ideas to make it easy and welcoming to bike, an important consideration for urban design because the more bike riders on streets, the higher perceived overall sense of safety for biking (Prato 2016).

The example of the Netherlands is useful here: more than one-quarter of all trips are made by bike, compared to only 1% in the U.S. (Miller, et al. 2013; Kuzmyak, Richard, and Dill 2012). The country has made substantial investments in bike infrastructure, safety, and comfort to arrive at such a high bike usage level (Miller, et al. 2013). Even though helmet wearing is rare in the Netherlands, the remarkable statistic is that a bike rider is actually 27 times more likely to get injured in the U.S. (Miller, et al. 2013).

While on the topic of walking (or skipping) and biking, it is worth considering how such non-motorized transportation might occur on the surface of Mars. With all the hazards outlined above and the demands for smooth or semi-smooth paths, it is easy to rule out any significant bike transport system on the surface. However, pedestrian travel on the surface would be possible with the use of extravehicular activity (EVA) suits (Clark 1996). These spacesuits are pressurized and include portable life support systems, making it possible for a person to hike up to 15 km in a day (Clark 1996). Given the high costs and bulkiness of EVA suits, the limited range they provide, and the risks associated with running low on life support systems, such pedestrian excursions on the Martian surface will not be considered as a realistic mode of regular travel. Instead, such surface hiking will be limited largely to short-duration recreation and exploration, at least in the early decades and centuries of human settlement on Mars.

Questions around access and adventure can shape human movement on Mars, but the more central task for urban planners is to consider the primary ways that people will move about – and that will need to be underground. That is why a well-thought, carefully designed subsurface bike network on

Mars can support multi-modal transportation and result in health benefits and better safety outcomes over the prevalent mobility systems currently in place on much of Earth.

Surface Road Transportation

This chapter suggests an underground mass transit network with a complimentary pedestrian and bicycle network, with full and complete connections within the Mars city and with links to other future settlements, spaceports, and distant locations. The planet's surface then becomes an appropriate place to install an impermanent and flexible network of roadways for rovers. Distinct from Earth's automobiles, rovers are rugged and not in need of well-maintained and smooth roads. An analog on Earth might be the snow vehicles and their roadways, which traverse Antarctica and the Arctic Circle.

The polar regions have taught us much about some of the key considerations for the construction and maintenance of such surface roads. First, the ground must be smooth enough to drive over (nowhere near as smooth as the Autobahn in Germany), but free of obstructions (like boulders or loose rocks) and not so bumpy as to damage the rovers (Adam and Hernandez 1977; Shoop, et al. 2016; Clark 1996). Second, the ground must be strong and secure enough to support rover traffic, which means it must be able to carry heavy weights over time without serious compression or sink holes. This may be a particularly thorny challenge in Mars because its soils appear to "have very poor load-bearing capability" (Clark 1996, p. 446).

In the Earth's polar regions, compact snow has generally been seen as the best avenue for preparing roadways (Shoop et al. 2016). Through a variety of techniques, roads are constructed this way to accommodate heavy weights across the entire roadbed. Again, these roadways are not smooth, but they provide safe passage around polar regions. Snow is not an obvious answer on Mars, but the assembly and compression of regolith using similar snow compaction methods can create roads on the Red Planet. Shoop et al. (2016) have also recommended the use of high molecular weight (HMV) sheets on roadways to enhance compression, improve traction, and better distribute weight across the roadway. And then there is the example of the settlement of Inuvik in the Northwest Territories of Canada, where water is poured along the surface of a roadway to a thickness of 13 centimeters, followed by a light sanding to improve traction (Adam and Hernandez 1977, 16). Given the frigid temperatures at that latitude, the liquid water quickly freezes when poured on the roadway and the application of sand results in a safe and durable roadway for

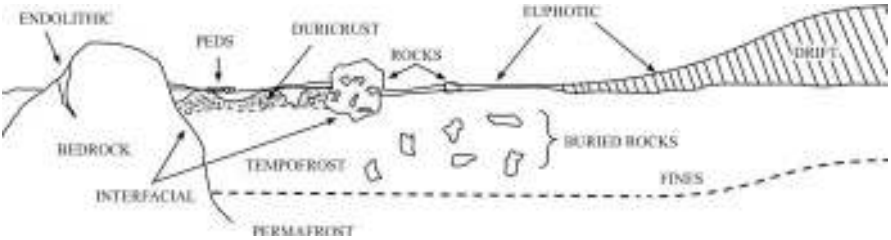

Figure 5.9: Schematic of terrain types on Mars (source: Elli Sol Strich, adapted from Clark 1996).

passage. Depending on how prevalent water is on Mars, this may also be a worthwhile approach to surface road construction and maintenance, just a little bit slippery during the warmer weather daylight hours.

Ultimately, the goal would be for these Martian roads to be rough marked lanes that can direct rover drivers around the city and make connections afar. Rover travel will certainly be a relatively dangerous mode of travel, with life support systems subject to running low and the wide range of hazards on the landscape that might cause a rover to become disabled or fall into an obstacle trap. These hazards, along with poor soil strength, the prevalence of boulders, and other wild variations in terrain (see Figure 5.9) prompted Clark (1996) to write that the rover pilot "will need not only driving skills but also the scientific expertise of the geologist, the skill of the mountaineer, and the perceptions of the explorer" (p. 446). Fortunately, these roads would be intended only as a tertiary level of transportation, allowing most people to travel by the primary and secondary modes described above. As such, surface road investments would need only be made at minimum levels to ensure safety and a modicum of comfort.

Transportation Principles

As Pardo (2010) writes, "the lack of comprehensive planning of transport systems [on Earth], without due consideration to social, economic and cultural elements of the city, can result in physical breaks in the fabric of communities and reinforce social exclusion" (p. 1-2). This chapter has introduced the three major ways that humans tend to get around a city on Earth, offering some insights into the ways that the Martian city of Aleph might learn from those examples. Based on the evidence presented in this chapter, transportation principles to be employed in the Aleph design will include:

1) Adoption of a primary mass transit that uses multiple tracks and is underground
2) Development of a secondary pedestrian and bike transport system that is underground
3) Creation of a tertiary rover system that relies on rough surface roadways

Together, these systems will serve as the foundation of Aleph city's design, answering Pardo's challenge in a way that promises an intact fabric of community and social inclusion. This three-tiered approach to transport also needs to be considered in light of other types of infrastructure –the focus of Chapter 7. Energy sources and utilities will impact the effectiveness of any motorized transportation, while telecommunications and any mass transit that links externally needs to be fully integrated (Lindgren, et al. 2009).

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6

Residential, Commercial, and Industrial Dimensions

The transportation considerations introduced in the last chapter provide a skeleton from which the bones, muscles, and tissue of a Martian colony can be created. This chapter examines the residential, commercial, and industrial uses that can be laid upon that skeleton. The next two chapters look specifically at other non-transportation infrastructure and building science. While these four chapters are separate, the overall plan for the first city on Mars, Aleph, needs to consider all of these dimensions holistically. Chapter 10 will weave together the principles introduced in these chapters and demonstrate how each one reinforces the others.

On Earth, decisions about transportation drive decisions around land uses, and the same should be expected on Mars. The introduction of a new bus route near my home makes getting to a nearby train station easier and drives demand for new housing uses across the street. More people and more housing spurs demand for commercial uses like restaurants and dry cleaners. As people flood into my neighborhood, industrial operations may begin to see opportunities for opening a new manufacturing plant where a highly skilled workforce appears to be growing.

Transportation is not the only driver of new land uses. Residential, commercial, and industrial uses can likewise serve as magnets (or repellents) for other uses. For example, that new factory might generate unpleasant odors and dampen demand for residential uses. In a capitalist, market-driven economic system, there are innumerable factors that causally string together various uses and infrastructure investments. The precise political-economic system of a Martian colony is hardly settled, though given the current nations

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Springer Praxis Books, https://doi.org/10.1007/978-3-031-07528-5_6

at the forefront of colonization, I am proceeding with an assumption that the system will resemble that employed in Antarctica.[1]

The Antarctic Treaty of 1959 lays out the political, legal, and economic system in place on the continent. A total of 48 countries are signatories to the treaty and a smaller subset of 28 have real political power, including the ability to create something the treaty calls National Antarctic Programs (NAPs). The most unique quality of the Treaty is that it forbids any single country from laying claim to any territory or asserting sovereignty over the lands. Activities on Antarctica are expressly reserved for peaceful purposes and research (Scott 2003). Legal oversight is left to the country from which any offender hails, while all countries reserve the right to monitor each other's responses to criminal and civil matters.

The Treaty was updated in 1991 through The Protocol on Environmental Protection to the Antarctic Treaty, which laid out detailed steps for environmental impact assessments, waste disposal, and waste minimization. The Protocol provides a framework for planning, development, and management of the built environment in Antarctica (Rothwell 2000). Each country, through its NAPs and the Protocol's guidance, develops overall plans for new development projects, which are subject to review by an International Steering Committee (Barret 1997).

With a collaborative, mutually supportive model like Antarctica in mind, where common values around peaceful scientific research are expressed through detailed guidance on planning and development, this chapter projects a range of constraints and opportunities for residential, commercial, and industrial uses on Mars. It later turns to the question of how various uses are mixed on Earth, then moves to the specific range of commercial and industrial uses that might be suitable on Mars, and concludes with a consideration of siting and design.

Mixing Uses

For much of human history, a chapter like this, examining uses like residential, commercial, and industrial as unique concepts, would have been viewed as bizarre. As Chapter 2 revealed, the earliest cities of Greece, Rome, and China mixed such uses very tightly into cities. Such mixing continued

[1] Elon Musk and Jeff Bezos have both advanced very different proposals for organizing social and political life on Mars. It should be noted that most of their spacefaring work to date has been accomplished in partnership with the U.S. Government, whose exploration of Antarctica is a reasonable predictor of how Martian colonization might occur.

unabated with the colonization of the Americas in the 15th and 16th centuries and Oceania into the 20th century. The archetype medieval European village consisted of high-density housing, metal smiths, trading posts, hog farms, and everything in between, packed together with no clear delineation of uses (Chapelot and Fossier 1985). Laws began to restrict loud, noxious, or odorous industrial uses from operating in close proximity to residential uses as early as the 13th century (Bermingham and Brennan 2018). But with the advent of the Industrial Revolution in England, industrial activities became drastically more disruptive, and the economic expansion associated with these activities brought heretofore unimaginable crowds into cities (Hall 2014). The crowding of English, European, and American cities in the 19th century was quickly followed by similar crowding patterns in cities across the globe, necessitating a new kind of thinking around urban management.

The result was the birth of modern city planning, and its hallmark was the separation of uses (Hall 2014). In 1916, New York City introduced its zoning code, and standard language of use categories was hence emulated by hundreds (if not thousands) of local governments the world over (Hirt 2007). The basic logic is that separate zones would be created for each of the three uses – residential, commercial, and industrial. Scores of additional subcategories could be created within each, broken down by more narrow uses (e.g. retail and office within commercial) and by density (e.g. single family home zones and apartment building zones within residential). While largely effective in curtailing the spread of unpleasant sights, sounds, and odors from industrial zones into residential and commercial ones, the broader architecture of zoning has been widely criticized as artificially dissecting otherwise integrated human activities like living, shopping, and working (Hirt 2007; Kunstler 1994). Instead, these critics argue for mixed-use development, where residential and commercial uses are fully integrated (Hirt 2007). In some cases, light industrial uses (like warehousing or microbreweries) have been brought into mixed-uses regulations (Cotter 2012).

There are two ways to think about mixed-use: Horizontal Mixed-Use (HMU) or Vertical Mixed-Use (VMU). In an HMU development, a hair stylist shop might be located next to an apartment building and across the street from an office building. In a VMU development, retail or restaurant uses might be on the first floor, while the second could include professional offices, and the third floor could house apartments (see Figures 6.1 and 6.2). VMU can offer much greater density, higher integration between uses, and easier connections with public transit – not to mention the attractiveness of building tall, given the substantially lower gravity on Mars than on Earth.

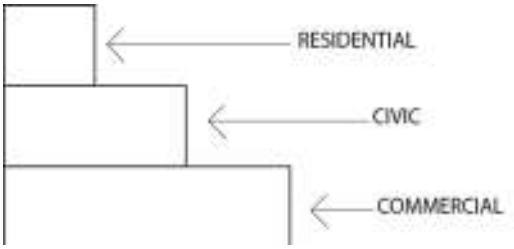

Figure 6.1: Vertical Mixed Use (source: Berk Diker).

Figure 6.2: Example of Vertical Mixed Use (VMU) in downtown Kirkland, Washington, USA (source Brett VA; Albert Herring (uploaded) / CC By-2.0).

Commercial and Industrial Uses on Mars

Few places on Earth resemble Mars in any meaningful way, with the exception of the most remote and inhospitable deserts and the Antarctica continent. In developing a plan for the colonization of Mars, it is essential to have some sense of the range of commercial and industrial uses that would be possible or even desirable.

Philip Harris (2009) in his *Space Enterprise: Living and Working Off-world in the 21st Century* suggests mining, tourism, and research to be the initial key commercial and industrial uses on Mars, later expanding to trade among Martian settlements and to Earth. Mining on Mars has become somewhat of a default activity driving the economy in countless science fiction novels,

films, and the imagination of serious space scientists (Abbot 2016).[2] Robotics research suggests that mining Mars could generate all of the raw materials needed to build a vibrant civilization, including "all the elements of industry, such as iron, titanium, nickel, zinc, silicon, aluminum, and copper" (Zubrin 2013, p. 2). If successful, this mining could eventually be the impetus for trade, first within Mars among settlements and then back to Earth. This is especially likely if extremely precious and in-demand metals appear in abundance on Mars.

The interest at the time of this writing for space tourism is extraordinary, and such demand would be expected to be high for a trip to Mars. The first non-astronaut to go into space was a Japanese journalist, whose employer, the TV station TBS, paid $12 million for the ride in 1990 (van Pelt 2005). He was quickly followed by a British citizen, Helen Sharman in 1991, then the self-made millionaire Dennis Tito in 2001, who paid $20 million, and then another millionaire, Marc Shuttleworth (van Pelt 2005). Virgin Galactic has also made a big splash with its own launch of a space tourism flight in the summer of 2021, followed shortly by Jeff Bezos' ride on his Blue Origin rocket into low-Earth orbit. With annual global travel expenditures exceeding $3.4 trillion and the smaller adventure travel segment topping $120 billion annually, interest is brewing for space tourists (van Pelt 2005).

A thought leader in space tourism, Michel van Pelt (2005) laid out his vision: "similar to terrestrial tourism, space tourists will follow in the wake of professional explorers, in this case astronauts, to the Moon, Mars, and further into the solar system" (181). He believes that visitors would travel the 50 million miles to see Mars with their own eyes, to gaze upon the 2,500-mile canyon Valles Marineris – the largest in the Solar System, as deep as 4.3 miles, compared with the Grand Canyon on Earth, which gets to only 1 mile deep – or to behold Olympus Mons, the largest mountain in the Solar System at 16 miles high (van Pelt 2005).

The arrival of tourists means that the City of Aleph needs to accommodate visitors, providing their housing, food, entertainment, and other needs (Utrila and Welsch 2017). However, these space tourists would bring with them resources to either pay for or barter for goods and services, serving as a potentially vital economic engine for the city. This raises the question of money – not something I will settle here, but a key question that needs to be addressed in any colonization plan.

[2] An incomplete list of writings and movies that feature mining activities on Mars includes: *Red Mars* (1992), *Total Recall* (1990), *Red Planet* (2000), and *Red Rising* (2014).

The third broad category of commercial and industrial use envisioned on Mars is scientific research. On Antarctica, it is research that sustains the economic life of the continent. Funding from both private and public sources seeks to understand a broad range of climatic, geologic, biologic, chemical, astronomical, and physical dimensions of science and engineering, employing the extreme cold and barren landscape of Antarctica to accomplish it. Likewise, science and engineering experimentation opportunities on Mars would be unprecedented. The Red Planet's unique environment and location in the Solar System could attract research that seeks answers to Earth's own challenges or explore and study ever more distant celestial bodies. Some research may simply try to understand Mars for its own sake.

Put together, these research endeavors will require buildings, supplies, equipment, transportation, housing, food, and fuel. Just as the City of Aleph would need to prepare for tourists, the same goes for the army of scientists, engineers, scholars, and support staff that would arrive for research-oriented missions. The funding that undergirded this research would be a key foundation for the economy of Aleph. It would generate demand for numerous ancillary commercial and industrial activities to support it, creating, with mining and tourism, a complete market-driven economic system with a myriad of actors, funding sources, and, in turn, the need for trade among Aleph and other future Mars settlements, as well as with Earth. The plan for Aleph needs to take this dynamic economy into account when considering the placement, location, and allocation of space for residential, commercial, and industrial uses.

Siting and Design Considerations

The siting and physical design of residential, commercial, and industrial uses on Earth requires sensitivity to topography, microclimate (e.g. winds and solar orientation), energy use, and comfort levels for occupants. In a temperate environment, mistakes around siting and design can mean mild annoyances, extra costs, and waste. In the most inhospitable locales, such sensitivity is heightened, and poor planning can mean the difference between life and death.

Some of the coldest, most mountainous regions on this planet have developed over centuries specific building and engineering systems to survive (Davies 2015; Matus 1988; Mänty and Pressman 1988; Nikpour, Kazemian, and Bahmani 2011).

Norman Pressman's (1988) research on what he called "winter cities" focuses on those places that experience prolonged periods of below freezing temperatures, precipitation, restricted daylight hours, and seasonal variation – environments not so dissimilar to Mars (except for the precipitation) (11). For these winter cities, he calls for special attention to pedestrian protection, including covered arcades and galleries and underground walkways. Pressman (1988) also writes about the need for high-density mixed uses (as discussed above), in order to reduce the distances that people need to travel. To achieve these objectives, he identifies a number of urban design and planning strategies. He calls for the purposeful use of color, lighting, greenery, and civic art in these winter cities (Pressman 1988, 21). His focus on the visual environment, underground solutions, high density, and mixed-use all support the principles outlined earlier in the chapter.

Other scholars have studied the building-level issues of winter cities and concluded that responding to wind patterns, orientation to the Sun, and energy efficiency mean that certain siting (where on a building site the footprint of a structure is erected), form (the shape of a building), and bulk (how a building occupies a site) solutions are appropriate. Jull (2016) looked at the hamlet of Resolute in Canada, one of the coldest populated places on Earth (Environment Canada 2016), and called for low-rise buildings and a "closed-contour" system where structures form a continuous edge along a front of forbidding winds. A similar benefit was also seen in exterior wind-breaker building elements in research in Alaska (Givoni 1998).

Relatively short structures two to three stories tall are widely seen as important to prevent the Sun from being blocked and to give solar access to other areas, where rounded buildings can better resist the damage that high winds can cause (Givoni 1998). Likewise, innovations like a Double Skin Facade (DSF), where two layers of glazing are separated by an air cavity, can evacuate solar radiation, mediate temperature fluctuation, and conserve energy (Zhou and Chen 2010). A round dome, roughly two to three stories tall at its apex, using DSF or wind-breaker technology may be an effective way to respond to the cold climate on Mars.

Much of the winter cities literature focuses on using underground passages or structures, like Oslo's three-lane underground highway or Montreal's underground network of passageways. Digging is one way to get underground; another is the kind of blasting methods used in mining on Earth (Tatiya 2013). Unfortunately, this kind of blasting needs to be done prior to the establishment of any settlement because it is so dangerous (see Figure 6.3)

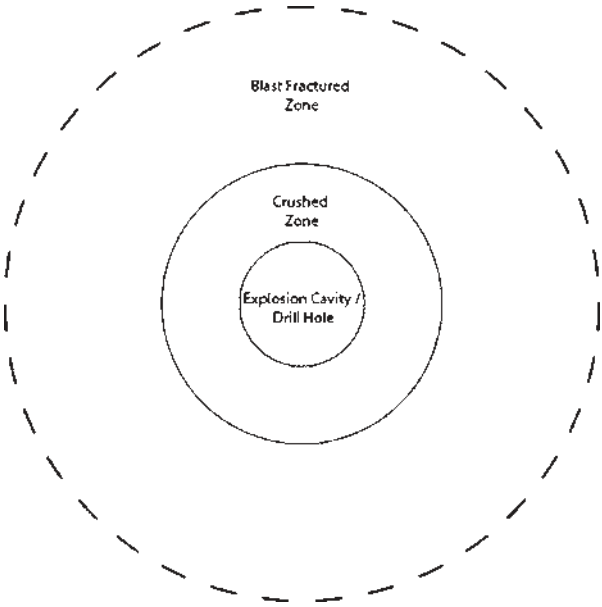

Figure 6.3: Diagram of the blasting method (source: Berk Diker).

(US Army Corps of Engineers 1972).[3] If such blasting is the first thing done in a new Martian settlement, it can be a cost effective and efficient way to go underground. Even better would be the adaptation of existing craters on Mars, like those caused by crashing asteroid or comets (Boston 1996).

Beyond simple tunneling, there is decent precedent on Earth for constructing underground buildings for residential, commercial, and industrial activities on Mars. In addition, building underground can achieve impressive efficiency over conventional building. A team of Malaysian engineers put it well: "the ancient wisdom of using the earth as temperature moderator against harsh weather has impressive potential to become a solid solution against the energy inefficiency of Heating, Ventilation, and Air Conditioning system (HVAC) in building" (Alkaff, et al. 2016, 692). Three broad categories of underground building are worthy of close examination: sunken courtyards, elevational plan, and cliff dwellings (see Figure 6.4).

Generated through extensive excavation or at naturally occurring depressions (or craters), the sunken courtyard concept involves building out living and working spaces underground, with a central "courtyard" exposed to the elements, but peripheral zones around the circumference of the courtyard reserved as protected zones. In Figure 6.5, illustrated examples of a rectilinear

[3] Blasting can cause flying debris, ground vibrations, and even disrupt underground rock formations (US Army Corps of Engineers 1972) and should not be done in any close proximity to human settlements.

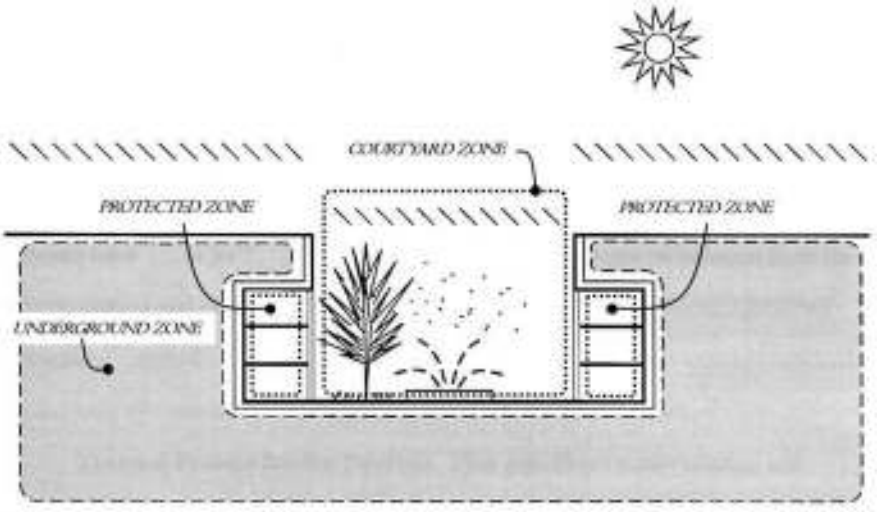

Figure 6.4: Diagram of the sunken courtyard concept (source: Al-Mumin 2001).

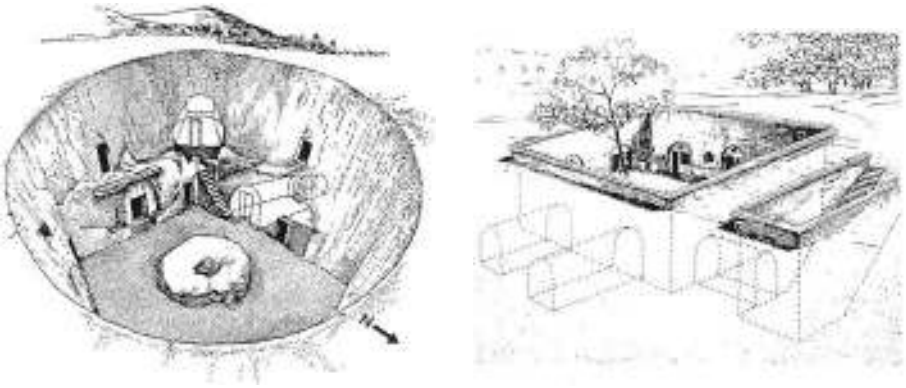

Figure 6.5: Illustration of a sunken courtyard in Matmata (source: Al-Mumin 2001).

and a semicircular courtyard from Tunisia and China are shown (Golany 1988; Golany 1992).

These building designs have been lauded as energy efficient compared to conventional buildings (van Dronkelaar, et al. 2014; Tafti, et al. 2018), and since the 1940s this ancient model has been emulated in new construction projects, like the addition to the Louvre and a new library at the University of Illinois (Al-Mumin 2001). U.S. architect Michael Reynolds founded a do-it-yourself Earthship-building movement, where structures are made from recycled and reclaimed materials and commonly built into cliffs, yielding impressive outcomes for heating and cooling performance (Ip and Miller 2009).

Van Dronkelaar, et al. (2014) found that ground property variation and variability in depth have little impact on the energy and comfort benefits of these underground abodes (p. 136). Others have calculated the ways that underground and partially underground buildings can better withstand natural disasters like fires, hurricanes, and tornadoes (Tafti, et al. 2018; Alkaff, et al. 2016).

The sunken courtyard design does have some drawbacks regarding light, lack of views, ventilation and humidity, emergency exit routes, drainage (less a problem on Mars), and structural stability (Alkaff, et al. 2016). Proper construction techniques can ameliorate the structural problems, but the other issues do present genuine challenges and can exacerbate psychological issues for inhabitants (Alkaff, et al. 2016).

Another approach to underground building is the elevational plan, as illustrated in Figure 6.6. Built into the side of mountains, hills, or (in theory) craters, these buildings can typically accommodate one to two stories, or more depending on the steepness of the slope (Alkaff, et al. 2016). Ancient examples can be found in Jordan and Iran (Alkaff, et al. 2016). The attractiveness of the elevational plan is that it does not require piling works, and soil that is excavated can be reused in shaping windows or roof members (Alkaff, et al.

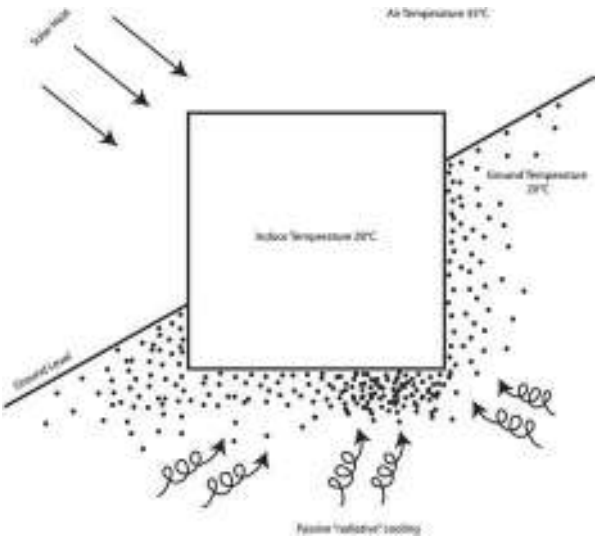

Figure 6.6: The effect of passive cooling in summer through the use of an elevational design (source: Aliya Magnuson, adapted from Alkaff et al. [2016])

2016). In addition, the design is viewed as more structurally sound regarding both the foundation and the roof structure than the sunken courtyard design (Alkaff, et al. 2016).

While not always underground, there is a long history on Earth of people building homes and work spaces in cliffs and caves. Cliff dwelling goes back at least 12,000 years, where rooms were carved into the sides of hills or mountains, some two to three stories high (Khodabakhshian 2016). Like underground structures, these dwellings were well insulated and had low temperature fluctuations; temperatures tended to be higher than outside in the winter and lower than outside in the summer (Khodabakhshian 2016). Examples of these kinds of structures can be seen in Maymand Village and Kandovan Village in Iran (Khodabakhshian 2016).

Examples in Iran show that people carved rooms into volcanic rocks, and the 7th century Cappadocia, Turkey caves house a sprawling indoor network going down eleven stories (Alkaff, et al. 2016). These caves were impressive feats that provided a range of uses, including churches, housing, storage, and more, serving an estimated population of 50,000 (Alkaff, et al. 2016).

Kozicka's (2008) paper in *Advances in Space Research* reviews these historic examples and draws several important conclusions, including

1) "natural slopes of terrain formation can act as the walls of the habitat" (p. 129-130);
2) impact craters exist on Mars that closely resemble those on Earth, where "it seems that some architectural solutions known and well developed on Earth can be successfully adapted… in a crater formation" (p. 134); and
3) settlements along terraces or in craters can be covered by a roof that "can be sealed with transparent multilayer membrane of a high resistance, providing natural light…" (p. 134).

Kozicka and Kozicka (2011) took these conclusions further by sketching out a design for a Martian base that employed the dome concept, but without employing craters.

In sum, the geothermal and light exposure benefits of the sunken courtyard, combined with the in situ and structurally advantageous elevation and cave/cliff dwelling designs, represent an ideal solution to the Mars climate and topography, especially if an appropriate existing crater can be identified for settlement building.

Radiation: Hazards and Protective Measures

In Chapter 1, I offered a brief overview of the threat posed by radiation on Mars. Even moderate exposure to the Sun's radiation on the surface of Mars could be fatal to humans (Cucinotta, et al. 2013; Cucinotta, To, and Cacao 2017). Despite decades of compelling evidence, much still remains unknown about what risks humans would actually face on a trip to Mars or living there (Chancellor, et al. 2018).

Some context around the scale of the radiation hazard is helpful. The average Earthling receives 0.0062 Sv/year of radiation – half from naturally-occurring background radiation and the other half from human-generated sources (U.S. Nuclear Regulatory Commission 2021). A *Sievert* (Sv) is a unit of measure for radiation's impact on the human body. In 1996, the Space Studies Board recommended a maximum dose of 0.5 Sv/year for those venturing off the planet and a maximum career exposure of 1-4 Sv (Jablonski and Ogden 2010, p. 461). There is increased risk of living on Mars compared to living on Earth, as illustrated in Figure 6.7. The radiation exposure of

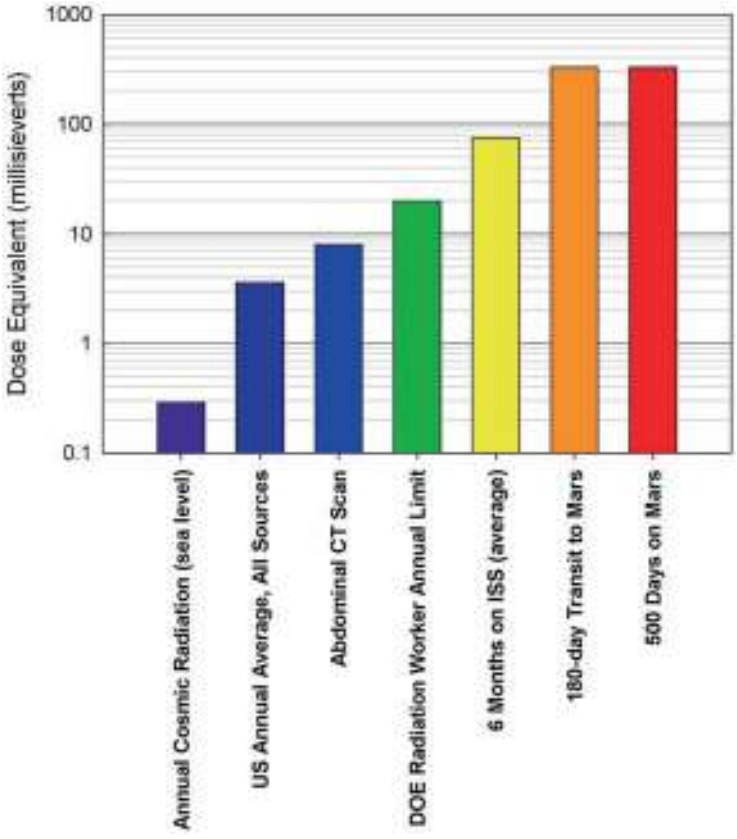

Figure 6.7: Radiation exposure comparison on log scale (Impey 2019; NASA/JPL-Caltech/SwRI).

spending 500 days on Mars might be 50 times that of an abdominal CT scan, but such higher Sv levels do not translate to an equally increased cancer risk. The risk of dying from cancer on Earth today is around 21%; living 500 days on Mars would only increase that chance to 24% (Impey 2019, p. 97). All of that additional exposure to radiation is expected to translate to a 14% increase in the likelihood of dying from cancer (Impey 2019).

Measures can be introduced to reduce that exposure, through protective clothing and aboveground structures (NASA 2017). In particular, buildings can be very effective in protecting people from the regular stream of solar particles emanating from the Sun. More challenging are the less regular, but more potent solar flares or coronal mass ejections that take the form of galactic cosmic rays (GCRs), which are much harder to shield against (NASA 2017). Kozicka and Kozicka (2011) explain that dosage matters: "GCR particles deliver lower dose of radiation. However, they reach the surface of Mars constantly. During solar events large proton flares deliver a very high dose radiation. Those events usually last only about a few hours" (p. 2001).

Two key questions linger for potential Mars colonizers: 1) What measures have scientists and engineers employed to protect humans from radiation exposure in mines, the International Space Station, airplanes, and elsewhere? And 2) What about solar radiation in particular? What materials or construction techniques are most effective at protecting people from a) solar particles and b) galactic cosmic rays?

Overall, humans have devised a range of techniques to protect ourselves from radiation. Many of the most advanced are codified by the National Council on Radiation Protection Measurements in scores of reports published over the years. Along with the U.S. Environmental Protection Agency (2006), these government reports largely recommend that in mining operations, techniques like dry-cover and water-cover systems be used to provide a physical barrier between radiation and people (National Council 1993). Similarly, in medical and diagnostic procedures, high atomic numbered materials like lead are used to create a physical barrier (Seeram 1999) – like when you go to the dentist and you are given a lead apron during X-rays of your molars.

The other major category of protection we presently use against radiation is based on avoidance. For example, in the aviation field, high-radiation flight routes are closely tracked, and alternative lower radiation routes are recommended (Bartlett 2004). For the International Space Station, NASA developed its "as low as reasonably achievable" (ALARA) model that seeks to employ some protective materials but relies largely on minimizing astronauts' radiation doses through an elaborate schedule and spatial configuration of activities (Shavers 2004, 1333). By monitoring and managing radiation exposure, astronauts can go about their business while staying healthy.

On Mars, it is equally possible to monitor and manage radiation exposure through a variety of avoidance strategies, e.g. timing surface-level work when radiation levels are low and carrying an emergency radiation shelter when venturing outside any habitats (Genta 2017). But that persistent threat of solar radiation is best addressed through physical shielding.

One study found that 40-80 g/cm^2 of HDPE (high-density polyethylene) would be the minimum material and thickness needed for a safe 500-day mission to Mars (Barthel 2018, 262). Another scientist reported that elements like hydrogen, as well as other substances that have high amounts of hydrogen, like water, are ideal for building physical barriers to both solar particles and GCRs (Genta 2017). Martian regolith has been identified for its protective qualities, though one engineer recommended a regolith simulant/polyimide composite as the best material to protect against GCRs.

Kozicka and Kozicka (2011) offer the most convincing recommendations for constructing these barriers. They call for a layer of Demron to be installed in the dome structures of their proposed Mars habitat. Demron is a widely used radiation protection material made from a proprietary non-toxic polymer. It is considered comparable to lead in its performance, but considerably more flexible (Radiation Shield Technologies 2020). Because solar events of large doses of particles can be predicted weeks in advance, the avoidance schemes described earlier can be a major element of protecting humans on Mars. For such events, people can move to a special shelter room surrounded by water or other materials with high hydrogen content (Kozicka and Kozicka 2011).

While radiation represents a severe hazard to life on Mars, there is an important paradox here: solar exposure for heat is a requirement in the cold climate of Mars (Cohen 1996). We want the sun's rays for warmth, but not solar particles and GCRs, so any habitat needs to strike a balance between protecting people and providing avenues for solar heat and warmth.

While it may sound like science fiction, NASA is exploring the possibility of mitigating radiation risks on Mars at the planetary scale through a massive magnetic shield (Williams 2017). At a NASA workshop "Planetary Science Vision 2050 Workshop" in the Spring of 2017, Planetary Science Division Director Jim Green publicly shared the proposal to install a magnetic dipole shield that would encompass the planet and shield it from solar wind and radiation (Williams 2017). Located at Mars' L1 Lagrange point, the artificial magnetosphere would reduce much of the threats from radiation discussed earlier. Dr. Green explained:

> This new research is coming about due to the application of full plasma physics codes and laboratory experiments. In the future it is quite possible that an inflatable structure(s) can generate a magnetic dipole field at a level of perhaps 1 or 2 Tesla (or 10,000 to 20,000 Gauss) as an active shield against the solar wind. (Williams 2017)

The shield could also thicken the Martian atmosphere, causing global warming of as much as 4 degrees Celsius – making Mars an overall much more hospitable environment for settlement.

As with anything we do on Mars – whether it be the kind of massive terraforming proposed by NASA or the smaller radiation mitigation measures– careful planning ahead of time, thoughtful analysis, and strategizing will mean the difference between a Jamestown, Virginia and its quick demise and a New Amsterdam and its hundreds-year-old success. As we contemplate the various residential, commercial, and industrial dimensions of life on Mars, the following principles help keep us focused on the big picture and provide planners with the tools to design a holistic, comprehensive, and safe settlement on Mars.

Principles for Residential, Commercial, and Industrial Dimensions

1. Design for high-density, mixed-use development.
2. Initial commercial functions can include mining, tourism, private research, and support functions. Over time, settlements could be developed enough to get involved in trade operations within their own borders and with other settlements.
3. In regions with extreme climates, access to amenities must be incorporated into the design from the beginning rather than being introduced at a later date.
4. Extreme climates demand compact and intensive textures, small and enclosed areas, narrow passages along the ground level, and layouts that take advantage of the position of the Sun.
5. The settlement must be hermetically sealed to protect the residents from the hostile atmosphere outside (to be discussed in greater detail in Chapter 7).
6. Radiation exposure on the surface must be taken into consideration when designing structural openings and exposed surfaces.

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7

Building Science, Design, and Engineering Beyond Earth

The previous chapter provided an overview of the residential, commercial, and industrial dimensions of planning a city on Mars. Here, I offer a closer view of the buildings themselves. What kinds of structures are built in Earth's most inhospitable environments? And what about space architecture itself? What has our experience designing and building habitats for people beyond Earth taught us about Martian building science, design, and engineering? While outer space habitats have been limited, people have experimented extensively with constructing analogs on Earth. What can we learn from that research?

In this chapter, architectural science, material science, and engineering insights will be presented, alongside four in-depth examinations of speculative designs for buildings on Mars. Where the rest of this book is focused on the broader urban realm and city design, this chapter explores what individual structures in Aleph City might look like, what materials they will likely be constructed of, what form they will take, and how they will be built.

Building in Extreme Climates on Earth

I introduced the Antarctic Treaty in Chapter 6, explaining how international cooperation has shaped the residential, commercial, and industrial land uses on Earth's southernmost continent. But the Treaty said little about building design or architecture, leaving those choices to the intrepid nations who have established year-round scientific research stations there. A close look at the U.S.'s McMurdo Station offers a window into building science in one of the coldest climates on the planet.

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J. B. Hollander, *The First City on Mars: An Urban Planner's Guide to Settling the Red Planet*, Springer Praxis Books, https://doi.org/10.1007/978-3-031-07528-5_7

Antarctica faces some of the same extreme cold temperatures seen on Mars (though not *as* cold!). It also faces the problem of snow. Much of McMurdo's building designs take this snow into consideration, including elevated structures on pillars to minimize the impact of snowdrifts, the rounding of corners to reduce snowdrift accumulations, and aligning buildings with the primary wind directions (Sanz Rodrigo et al. 2012). Other Antarctica designs provide benefits against snow and cold, like the igloo, which maximizes the surface-to-volume ratio in a manner that best minimizes heat loss (Davis 2015) (see Figure 7.1). But not all McMurdo designs reflect this kind of proactive thinking: the reality of the base is that "boxy building or offshoots from a single spine…prevail mostly because they are easy to design, transport, and construct" (Davis 2015, p. 52–53; Davis 2017). This is a critical point – that in spite of potential benefits that certain designs might offer for extreme cold, the ease and economics of conventional building design win out more often than innovative curved edged or domed structures (see aerial view of practically all conventional buildings at McMurdo Station in Figure 7.2).

McMurdo is a rapidly changing place: "few of McMurdo's old buildings remain; 100 structures have already been removed. Rapid deterioration, technological advances, changing needs, restructured management, and expansion of research all drive continual redevelopment of the station" (Collis and Stevens 2007, p.245). The erection of temporary and inexpensive structures

Figure 7.1: Dome-shaped igloos in traditional Inuit village, circa 1865. This image is a photograph of a book illustration depicting the village of Oopungnewing, near Frobisher Bay on Baffin Island (source: Unknown artist based on sketches by C.F. Hall and published in Arctic Researches and Life Among the Esquimaux: Being the Narrative of an Expedition in Search of Sir John Franklin in the Years 1860, 1861, and 1862 by Charles Francis Hall, uploaded by Finetooth / PD – Art).

Figure 7.2: Aerial view of McMurdo Station in Antartica (source: Ralph Maestas, National Science Foundation / Public Domain).

Figure 7.3: The administrative headquarters for the National Science Foundation, known as the Chalet, is unique among McMurdo Station's structures (source: Peter Rejcek and National Science Foundation).

at McMurdo has meant that little attention has been given to embracing high-tech, cold-weather-resistant strategies. There is one notable exception: the Chalet (c. 1970) (see Figure 7.3). The Chalet serves as the National Science Foundation headquarters and features a pitched roof and the aesthetic of a Swiss Chalet – hence the nickname (Collis and Stevens 2007). Built to last and designed for a snowy climate, the Chalet serves as the symbolic center of the base. Its physical design and use of energy-efficient materials make it a

well-suited building for the cold Antarctic climate, but more than anything, its presence highlights how rarely such technologies are employed throughout the rest of the region.

Likewise, the inattention to aesthetics is linked to a broader psycho-social dystopia that some have reported existing at McMurdo (Johnson 2005). The remoteness of the base and its drab buildings contribute to a sense among some inhabitants that Antarctica is an unwelcoming continent, and that psychological hazards are more significant than physical ones (Johnson 2005; Khandelwal, Bhatia, and Mishra 2017; Jenkins and Palmer 2003).

There are exceptions. Elsewhere in Antarctica, architects, scientists, and engineers have experimented with a limited number of other building design forms and styles to achieve warmth for occupants. An international team erected their Polar Lab 2 (PL2) on King George Island in Antarctica in 2016, drawing on thousands-year-old technology developed in the harsh winter climate of Mongolia: the yurt tent (Andrews 1997; Silva et al. 2019) (see Figure 7.4 and 7.5). The design team focused on: maximizing the form of the yurt to withstand wind; being purposeful in orienting the door to reduce heat loss; and developing a triple-level wall system and insulated flooring to reinforce heat-maintaining elements of the building envelope (Roaf et al. 2019).

Outside of the desert environs of Antartica, extremely dry places have been home to human settlement for thousands of years. These arid environments also offer much to inform Martian architecture. In their 2014 guide, the Chartered Institution of Building Services Engineers wrote about strategies

Figure 7.4: Traditional fabric yurt from the Telengit people, Altai Republic, Russia (source: Alexandr frolov / CC BY-SA 4.0).

Figure 7.5: Modern Kazakh yurt similar to a design used by Polar Lab 2 in Antarctica (source: Alexandr frolov / CC BY-SA 4.0).

for building in extreme arid climates. They identified a number of important considerations, including the need to manage wind by orienting buildings towards the primary wind source direction. They also recommended erecting wind-catching towers, vertical structures that redirect wind flow away from human habitats (CIBSE 2014, p. 20). Interestingly, on Mars, drastically lower air pressure means that wind is a negligible concern for architects!

The Chartered Engineers also focused on how critical it is to maintain building thermal performance. In an arid and *hot* environment, this means keeping the hot air from getting inside, but in an arid and *cold* place, such techniques mean keeping the hot air generated inside from escaping. They recommend insulation in building walls, orienting structures towards the Sun for heat gain, and site layouts that maximize solar exposure. Lastly, the Chartered Engineers suggest that the heating and ventilation plant for a facility be located in a "relatively cool environment," even air conditioned – not so hard to accomplish on frigid Mars (CIBSE 2014, p. 63).

In sum, the lessons from extreme cold and from arid environments on Earth for Martian building design emerge largely from Indigenous societies' insights. It is the igloo and the yurt that appear as the most energy-efficient building forms for extreme cold climates. These spherical shapes offer the greatest protection against heat loss and can be effectively insulated. Orientating igloos and yurts to maximize solar exposure and heat gain will also deliver additional heating benefits. Ironically, modern construction in much of Antarctica has ignored this wisdom by building boxy, inexpensive,

energy-inefficient structures, suggesting that the ease of using conventional methods might also take precedence over any lofty (and untested) building designs for Mars.

Construction Materials, Form, and Methods

The construction process for Martian buildings is different in fundamental ways from how we build on Earth. In this section, I unpack the construction materials, forms, and methods of Martian building that can help inform the plan to be presented for Aleph City in Chapter 11. Earlier in the book, in Chapter 5, I wrote about transportation and explored how the Martian low-gravity environment might impact walking and biking. The challenges of low gravity and low air pressure will be addressed below.

Materials

An important component to any building design is the materials used. This is ever more important when those materials need to be shipped on a spacecraft across the Solar System or mined in situ. Lessons from polar and arid regions suggest that the materials employed really matter, and the difference in atmospheric pressure, gravity, and radiation between Earth and Mars also will have an important bearing on the types of materials needed.

In recent years, there has been a flurry of planning for new human landings and subsequent development of a permanent base on the Moon. While the climate, atmosphere, and gravity are quite different between the Moon and Mars, this research can offer useful insights. Firstly, metal construction is widely viewed as the most reliable material for extraterrestrial application, and many lunar building designs therefore use carbon steel, aluminum, titanium, and magnesium metals (Kozicka 2008; Ruess et al. 2018). The abundance of iron (explaining Mars' reddish hue) in the form of FeO2 suggests that in-situ utilization of iron for construction may be prudent (Sherwood and Toups 2001). Also used in these designs are different types of fabrics and membranes (notably Teflon), manufactured by companies like Birdair, Tefzel, and Foiltec (Kozicka 2008).

Given the high costs of transporting materials, many designers opt for in-situ resource utilization to generate construction materials for their proposed projects. While metals are quite ubiquitous in both lunar and Martian regolith, extracting and using them are seen as exceedingly complex and difficult

(Wilhelm and Curbach 2014). Instead, using onsite raw materials to create bricks, ceramics, glass, or different types of concrete is preferable (Wilhem and Curbach 2014). However, typical Earth-based methods for material formation need to be adjusted to fit the unique low gravity Martian environment – considering qualities like "multiphase flow, surface wetting and interfacial tension…[and] solidification" (Naser 2019, p. 100577). With some small changes, a material like concrete is actually better able to handle stresses for large buildings on Mars than on Earth (Cullingford and Keller 1992).[1]

With the vast supply of rocks and regolith on the Martian surface, this might be the most accessible of all in-situ building materials. Simply cutting regolith into small bricks or blocks would generate a readily available building material on Mars. This technique has a long tradition in human history, though it is highly energy intensive (Kozicka 2008). The inventor Ebrahim Nader Khalili filed a patent in 1999 that might offer a modest improvement on the brick system, while remaining simple and easy: what he calls "superadobe" involves placing soil (with modest quantities of cement and water) in long bags with barbed wire between. Polish architect and scholar Jan Kozicka (2008) writes about Khalili's idea favorably and argues that resin imported from Earth could replace water in the cement creation, offering an inexpensive and sturdy building material for Mars.

A simple and ancient heating process can transform regolith into glass, as experiments with lunar regolith have shown (Ray et al. 2010; Naser 2019). Astronauts found glass naturally occurring in lunar regolith, likely appearing due to the sudden heat caused by meteorites (or micrometeorites) or volcanic eruptions followed by a rapid cool-down (Naser 2019). And the glass showed up in not-so-small quantities: it comprised 6–92% of the total weight of a lunar regolith sample (Naser 2019, p. 6). Given the similarities between lunar and Martian regolith, glass production would allow for an ample supply of transparent building material, providing solar exposure to interior spaces and extraordinary views of the Martian sky (radiation concerns notwithstanding; see discussion in Chapter 6).

More advanced techniques can transform that same regolith into something even stronger than glass. Direct *sintering* – the application of extremely high heat to cause liquification – of regolith using microwave irradiation or a laser beam can create building-grade ceramic, while concrete can be generated through a mix of regolith or soil with sulfur (Wan, Wender, and Cusatis 2016;

[1] Another positive consideration is that cement dehydration does not occur in low gravity environments (Cullingford and Keller 1992).

Wilhem and Curbach 2014). Sulfur is highly abundant on the Martian surface and has been used as a "molten bonding agent" since antiquity (Wan, Wender, and Cusatis 2016, p.222; Naser 2019). Sulfur concrete has excellent characteristics for construction in extreme climates here on Earth, and those same characteristics give us confidence that it will perform well as a construction material on Mars. Sulfur concrete features high compressive and flexural strength, durability, acid resistance, and impressive freeze/thaw performance (Wan, Wender, and Cusatis 2016, p.222).

Likewise, cast basalt (a black, glassy material) can be processed from regolith through sintering, a fast process that creates high-strength bricks or slabs for construction (Naser 2019).[2] Other concretes may all offer some advantages and disadvantages in the still relatively unknown Martian environment (Naser 2019). Basalt fibers can also be manufactured using similar techniques and are considered quite durable; such fibers can be employed as reinforcing rods in concrete or for other building materials (Wu et al. 2015).

Early stages of Martian urbanization would benefit from the use of metals, fabrics, and membranes, but given the high energy costs and complexity of manufacturing those from in-situ resources, they would at first have to be brought from Earth. More advanced urbanization of Mars could involve such in-situ industrialization, but in approaching the design for the first city on Mars, using existing available materials makes more sense. Martian regolith can be cut to create simple bricks or be mixed and ground down using the superadobe method described above. Slightly more advanced and energy intensive sintering techniques can produce even sturdier bricks, ceramics, glass, and concrete, all from Martian regolith. We can expect the first city on Mars to be built from a combination of these in-situ resources and a more modest collection of metals, fabrics, and membranes brought from Earth.

Building Form

The form of Martian architecture has been considered by a number of scientists and engineers (along with a vast number of science fiction writers, whose opinions we will return to later in the book). Given Mars' atmospheric pressure and gravity, it is fair to presume that buildings might look different than on Earth. With Martian gravity only 0.38 of Earth's, structural design requires far lower *dead loads* – relatively constant weights like structural elements and flooring that weigh down a building and require substantial foundations to

[2] Research on the International Space Station has shown that mining basalt in low-gravity environments is feasible (Cocknell et al. 2021).

hold them up (Bucklin et al. 2001). As such, it is possible to use lighter and weaker structures on Mars than is possible on Earth (Reches 2019).

While atmospheric pressure varies across seasons and the geography of Mars, it is so low in comparison with pressure on Earth that it can be viewed as close to zero (Bucklin et al. 2001). But such a low-pressure environment is not suitable for human habitation, so indoor spaces need to be pressurized, which puts additional stress on building walls and roofs. Wide, flat roofs are particularly susceptible to these stressors, while cylindrical shapes appear best at handling this pressure differential (Sartipi 2021).

With low atmospheric pressure, one important Earth-based consideration – wind – can then be generally ignored in Martian architecture. On the other hand, the dust storms that regularly blanket the Martian surface do require that special attention be paid to keeping solar collectors cleaned, preventing dust from entering building mechanical systems, and keeping windows cleared (see Chapter 8 for more details on Martian dust devils).

Four unique forms for Martian building have been debated within the architectural engineering community: inflatables, cable structures, crater/cliff forms, and rigid structures. For each, a certain degree of modularity is expected so that segments of the buildings can be connected and interconnected as needed – something observed in a variety of Earth-based simulated Martian habitats, as well as both the ISS and the currently under-construction Tiansong space station (Heinicke and Arnhof 2021; Chen et al. 2021).

If you are in a hurry, an inflatable building is a good bet: it can be packed quite small in a spaceship, erected quickly on-site, and tends to be pretty inexpensive (Ruess et al. 2018; Häuplik-Meusburger and Bannova 2016). Inflatables are particularly easy to build modularly, making expansion easy (Häuplik-Meusburger and Bannova 2016). A notable example is the Inflatable Lunar-Martian Analog Habitat (ILMAH) developed by the University of North Dakota (Heinicke and Arnhof 2021). This simulated environment is an inflatable building that features a rigid internal frame (Heinicke and Arnhof 2021). NASA has also built its own inflatable buildings, including the Inflatable Lunar Habitat sited at McMurdo Station in Antarctica (see Figure 7.6 for photograph of the habitat prior to installation). While great for short-term visits, inflatables do not have long-term viability because they are constructed of fabrics and membranes that do not have the kind of durability of some of the other materials reviewed earlier.

Lunar base designs have considered cable structures, typically with stiffened trusses and reinforced fabrics as a more durable alternative to inflatables (Ruess et al. 2018). Like inflatables, cable structures pack small for the ride to Mars and can be relatively inexpensive and easy to erect. Cable structures are

Figure 7.6: NASA's Inflatable Lunar Habitat at NASA's Langley Research Center in Hampton, Virginia (source: NASA / Sean Smith).

widely used on Earth and are generally considered quite durable and safe, but they cannot be easily constructed from in-situ resources on Mars (Nowak and Collins 2012).

The forms discussed so far are all dependent on stand-alone structures, but building into the side of a crater or hillside can help distribute loads more effectively. The use of existing landforms can reduce the need for excavation and increase radiation protection for a building (Ruess et al. 2018). A plan advanced by Alice Eichold (2000) to build a lunar station relied on construction inside a small crater and noted that the crater walls also provided blast protection from nearby rocket launches.

Such crater-dependent forms tend to involve either the partial or full burying of habitats underground. There are benefits of placing buildings and people below the Martian surface in order to protect them from radiation and to benefit from the more consistent ambient temperatures belowground (see more on approaches to underground cities in Chapter 6). United Kingdom anthropologists David Jeevendrampillai and Aaron Parkhurst (2021) considered this option and opined, "For the architect whose vision of the future is premised on a particular configuration of humanness, moving underground – losing the mastery of the landscape – is a form of death, while for the biologist, it is a form of life" (p. 43).

The last form that might be considered on Mars is a "rigid structure." Within this category are domes, shell structures, and arches. These rigid

structures are distinctly robust and puncture-resistant (Ruess et al. 2018), quite different than the inflatables discussed earlier and not reliant on the kind of high-pressure tension needed for cable structures.

The dome is an ancient building form, yet considered futuristic at the same time (see Figure 7.7). In the first *Star Wars* film that was released in 1977, the protagonist Luke Skywalker is introduced to the audience while living with his aunt and uncle in an arid Tatooine agricultural community comprised of a series of domed structures with indoor farms.[3] From domed-shaped igloos to Buckminster Fuller's grand geodesic dome, humans have formed a long connection to this particular building form, and rightly so: it does not require centering in the construction process, and building can be paused at any point without compromising the stability of the structure (Kozicki and Kozicki 2011). In masonry construction, *centering* involves the erection of support systems that provide the form for an arch or vault before it can support itself.

With only minimal gravity and practically no wind concerns, the only dead load on a Martian dome comes from internal pressure (Bucklin et al. 2001). The dome just may be the best shape for a Martian structure based on its strength-to-weight ratio (Bucklin et al. 2001). Domes are also advantageous

Figure 7.7: The HI-SEAS Simulation Station on the Mauna Loa volcano in Hawaii features a dome (source: NASA).

[3] The *Star Wars* movie makers continued to reprise the Tatooine domes in future films. The newest film in the *Star Wars* franchise (as of the writing of this book) concluded with a dramatic scene at those same Tatooine domes (*Star Wars: The Rise of Skywalker*, 2019).

because they can be constructed from a wide range of materials, but typically have metal or concrete at their base (Kozicki and Kozicka 2011). Lastly, both igloos and yurts take on a dome shape, and lessons from earlier in the chapter suggest they are the ideal form for heat conservation.

Shell structures, another kind of rigid structure, can fully enclose a space and due to their rigid and solid qualities can block radiation for occupants (Yazici 2018). Shell structures can be made from brick or other types of building blocks (Yazici 2018). Arches are also a well-known building form that have a long history, considered by some to be the most efficient shape in architecture (Yashar et al. 2019). Arches that lean on each other are a design strategy for supporting pitched-brick vaults in a masonry Martian structure. Petrov and Ochsendorf (2005) explain it well:

> The first bricks on each side are laid at an angle against a sidewall; the second set of bricks is placed on top of the first, also leaning against the wall, and so on until the arch of the vault closes at the top. Successive arches are leaned on the first one until the end of the vault is reached. The remaining triangular space is filled in with smaller arches. Often, more courses are laid on top of the first one, leaning in opposite directions (p. 52–53)

Of course, a hybrid system may also emerge. Introduced in the previous chapter, Michael Reynolds' Earthship concept suggests that combining a mix of found, locally acquired materials, and manufactured framing or structural systems might serve Martian inhabitants well. These forms – inflatables, cable structures, craters/cliffs, rigid structures, and hybrids – each respond to materials available to the architect and are sensitive to construction methods available on Mars – which I turn to next.

Construction Methods

Extreme cold, near-nil atmospheric pressure, and drastically lower gravity than we find on Earth all impact construction methods on Mars. As mentioned earlier, the difficulty of bringing materials to Mars makes in-situ resource utilization an important consideration in choosing methods for building construction. Using Martian regolith can be valuable for masonry construction techniques (Petrov and Ochsendorf 2005). Through the layering of bricks, blocks, or stones with mortar, it is possible to quickly and safely build on Mars while relying almost exclusively on local materials (Kozicka 2008). Mortar is made of sand and water, though through experimentation

on-site, Martian construction crews may find that additives are necessary to respond to local gravity and atmospheric conditions (Petrov and Ochsendorf 2005). At some point, "mortar might be replaced entirely by polymer extracts derived from the inedible plant material that would be a by-product of the settlement's food production process" (Petrov and Ochsendorf 2005, p. 53). Masonry construction can be durable and, in concert with a tension pressure module system, can offer high-tensile strength (Petrov and Ochsendorf 2005).

There has been exponential growth in the recent adoption of 3D printing in construction here on Earth (Tay et al. 2017; El-Sayegh, Romdhane, and Manjikian 2020). Through a layering process, these printers can generate exceptionally complex shapes and geometries, generally up to one or two building stories (Wilhem and Curbach 2014) (see Figures 7.8 and 7.9). Part of a broader construction process known as additive manufacturing, 3D printing can automate and simplify building construction (Camacho et al. 2018). *Additive manufacturing* is widely synonymous with 3D printing in that it uses digital directions in the form of a 3D computer-aided design (CAD) model to direct a machine to manufacture an object by layering materials over each other in order to generate three-dimensional shapes.

The numerous advantages of 3D printing building components include enhanced efficiency, improved sustainability, and reduced human capital requirements (Tay et al. 2017; El-Sayegh, Romdhane, and Manjikian 2020). When first arriving on Mars, where few safety or medical resources are yet in place, human-operated construction methods are particularly hazardous.[4] For example, micrometeors could tear an astronaut/construction worker's suit and bring near-immediate death (Solanki 2015). As such, the automation of any early building on Mars is an attractive option.

Bringing a 3D printer capable of constructing large buildings on Mars would be a payload burden, as these machines are big and heavy (over four tons!). Unfortunately, extracting the natural resources necessary to manufacture a 3D printer on Mars would require the establishment of advanced industry and is not a likely option for the first city there.[5] So, until then, 3D printers would need to be brought from Earth.

The New York Times profiled the Vulcan II printer, which printed more than 200 small homes in a Mexican community, each taking less than 24 hours. The article explained that the printer was 11 feet tall and used concrete, foam, and polymers as raw materials (Kamin 2021). Icon, the

[4] Not only hazardous, but due to low gravity, digging into the Martian ground is even harder than on Earth (Hutson 2019).

[5] It appears that most of the known elements exist on Mars and "it should be possible eventually to make anything there that can be made on Earth" (Sherwood and Toups 2009, p. 177)

Figure 7.8: Italian 3D construction printer uses clay and other natural materials and the patented TECLA supporting structure. House designed by Mario Cucinella Architects (source: Constructed by Mario Cucinella Architects, video by Alfred Milano and Italdron / CC BY 2.5).

Figure 7.9: Single-family home built by the AMT 3D Construction Printer in Yaroslavl, Russia (source: AMT-SPETSAVIA Group (Russia) and OpenStreetMap / CC BY-SA 4.0).

Austin, Texas company featured in the article, is also working on a project with NASA and the global design firm Bjarke Ingels Group (BIG) to explore the potential for their Vulcan II printer to be used on Mars (Kamin 2021) (see a profile of their project later in the chapter).

Yashar et al. (2019) have written about the company Apis Cor's rotational gantry robotic arm, which can be mounted on a mobile platform and sent just about anywhere (including Mars!) A major advancement on conventional 3D printers, the robotic arm can drastically reduce construction costs and time (Camacho et al. 2018). Apis Cor's robotic arm is relatively light, only about 1.5 tons, and can build two-story buildings (Apis Cor 2021). Remember that early computers were quite massive and limited, while today, we fit brilliant machines that can outperform 1970s-era supercomputers in our pockets. By the time we settle Mars, it is a fair bet that additive manufacturing will have similarly advanced, and the size and weight of 3D printers will be reduced to the point where they are an attractive approach to constructing buildings.

Martian Architecture: Designs and Ideas

The nascent field of space architecture is almost entirely speculative. With the exception of the four small space stations[6] that have occupied low-Earth orbit at various time over the last four decades (discussed in detail in Chapter 3), humans have hardly ever lived in space, the Moon, or another planet. Space agencies, engineers, and architects have sketched out an untold number of proposed designs, with some even built as prototypes here on Earth. In this section, I review a selection of those designs to help illustrate the points above with respect to building materials, architectural forms, and construction methods. All of this is done to develop the series of principles that will feed into the plan for a city on Mars in Chapter 11. The following architectural designs reflect state-of-the-art knowledge around building science and engineering.

ZA Architects

The German architecture firm ZA Architects developed a plan for an initial Martian base in collaboration with the Dessau Institute of Architecture (DIA). Their base focuses on building underground spaces, protecting people from

[6] Skylab (1973–1974), Salyut 7 (1982–1991), Mir (1986–2001), and the International Space Station (2000-present).

radiation and putting them in an environment with a relatively constant temperature (Solanki 2015; Andrews 2013) (see Figure 7.10). They begin with the premise that advanced robots can be sent to Mars to excavate massive caves deep into the surface, while acknowledging that such robotics technology is not currently available ("ZA Architects reveal Mars Colonization Project" 2013).

ZA Architects was inspired by a Terran analog: the natural occurrence of caves that form from the rapid cooling of basaltic lava. The firm points to Fingal's Cave in Scotland: according to the National Trust for Scotland (2006), Fingal's Cave is known for its "distinctive stepped basalt columns, created when the lava from volcanic eruptions cooled many millions of years ago…These columns form the cathedral like structure of Fingal's Cave." This design fits most closely with the crater/cliff forms described earlier in the chapter, relying on the existing structure of the Martian geology to provide support for walls and roofs.

The German team proposes that a spaceship from Earth sends a team of intrepid robots to search out ideal locations on the Martian surface where such basaltic lava is believed to exist and then drill down "like ants" to open an underground cavern for human uses (Solanki 2015, p. 46). The excavation would retain a network of columns to support the subterranean rooms, and the robots would weave "web-like structures from basalt fibers to create floors within the caves. Basalt fibers, made by extruding molten ballast, are cheaper and more versatile than carbon fibers" (Andrews 2013) (see Figures 7.11,

Figure 7.10: Rendering of ZA Architects' Mars colony (source: ZA Architects, Dmitry Zhuikov and Arina Agieieva).

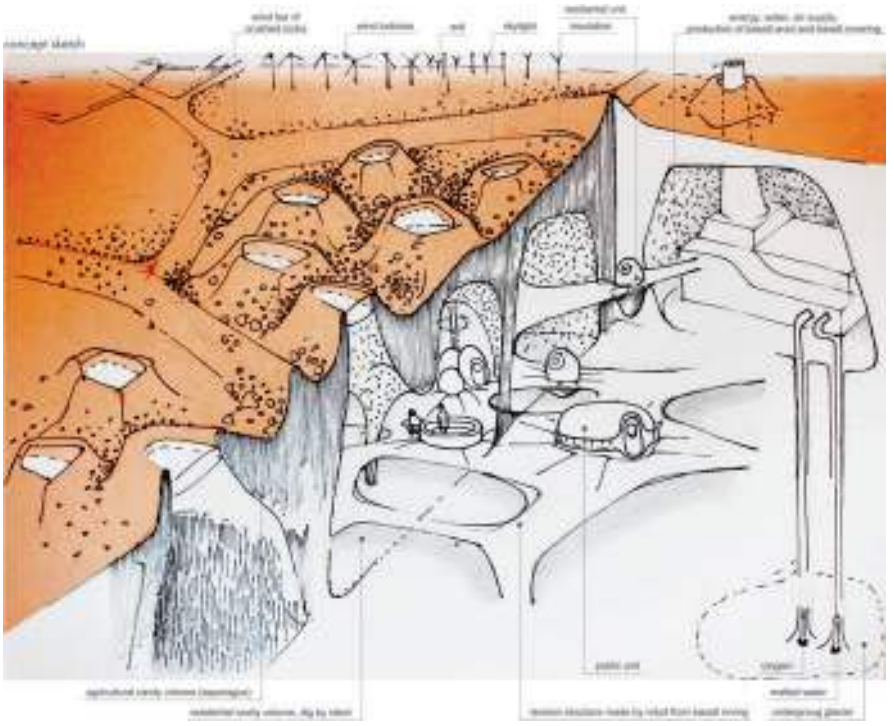

Figure 7.11: ZA Architects' conceptual sketch of their Mars colony (source: ZA Architects, Dmitry Zhuikov and Arina Agieieva).

7.12, and 7.13, and 7.14). Earlier in the chapter, basalt fibers were briefly discussed, and here they are employed in a novel way, using in-situ basalt rock to construct floors in an otherwise vast and open underground cathedral.

The design of the ZA Architects' Martian base addresses many of the problems faced by life on the Martian surface, but by putting people far underground, the team risks causing the inhabitants potential psychological harm. As I discussed in Chapter 4, the emotional experience of humans needs to be the first principle in designing cities on Mars, and while the ZA Architects' plan may be functional, it is not likely to create a happy environment for people.

Foster and Partners

World-renowned architect Norman Foster and his firm have been refining their vision for off-world buildings since they partnered with the European Space Agency on a lunar habitat design in 2012 (Koscher 2018). In a series of

Figure 7.12: ZA Architects' rendering of woven basalt-fiber flooring (source: ZA Architects, Dmitry Zhuikov and Arina Agieieva).

Figure 7.13: Interior rendering of ZA Architects' Mars colony (source: ZA Architects, Dmitry Zhuikov and Arina Agieieva).

competition entries and commissions, the firm has articulated a scientifically grounded approach for a habitat that could be developed on the Moon or Mars.

In four steps, the 93-square-meter habitats can be built with little human intervention. First, a series of entry modules are parachuted down to the Martian surface, where they begin to autonomously scout out and excavate their own 1.5-meter-deep crater (Frearson 2015) (see Figure 7.15). The existence of a multitude of craters on Mars might make this step seem

Figure 7.14: Rendering section of interior of ZA Architects' Mars colony (source: ZA Architects, Dmitry Zhuikov and Arina Agieieva).

Figure 7.15: Foster + Partners' plan for building structures on Mars: Step 1 involves the landing of robots on the Martian surface to conduct site preparation and excavation work (source: Foster + Partners).

superfluous, however, given the completely autonomous nature of the construction, the precise dimensions and structural quality of each crater must be preset to match the habitat equipment that will follow.

In the next two steps, inflatable habitat pods are parachuted down to Mars and then move themselves into the newly created craters, where they self-inflate and self-connect to one another via airlock (Koscher 2018) (see Figure 7.16). In the fourth step, small robots employ additive manufacturing

Figure 7.16: Step 2 of Foster + Partners' building plan for Mars: landing of the habitat units in craters excavated by earlier robots (source: Foster + Partners).

techniques to fuse regolith into concrete using microwaves (as mentioned earlier in the chapter), creating the rigid exterior protective shell for the inflatable habitats (Frearson 2015; Koscher 2018).

Here, the Foster team combines the inflatable form with the rigid structural form in an approach that eases construction and assembly and also results in a durable design that can protect inhabitants from radiation and other outside hazards (see Figure 7.17). The final design is dome-like in form but is really a shell structure comprised of layered walls of regolith-based concrete (see Figures 7.18, 7.19, 7.20, 7.21, and 7.22). Most notable in these final designs is how little sunlight they allow into the interior. With few exterior openings or windows, they create the same psychological challenges seen in the ZA Architect's design. Nevertheless, the Foster + Partners design is a spectacular expression of the science and engineering ideas explored in this chapter, reflecting the state-of-the-art in what it means to design a building on Mars.

BIG

As mentioned earlier in this chapter, the design firm Bjarke Ingels Group (BIG) has teamed up with the robotics firm ICON to develop a project they call Mars Dune Alpha habitat for NASA (D'Angelo 2021). They are using the

Figure 7.17: In Step 3, habitat modules are deployed and inflated and connected to one another via airlock (source: Foster + Partners).

Figure 7.18: Step 4: Using 3D printers, the habitats are constructed (source: Foster + Partners).

3D printer Vulcan II to create a 158-square-meter rectilinear structure inside NASA's Johnson Space Center in Houston, Texas (see Figures 7.23 and 7.24). NASA is now recruiting astronauts who will live in the habitat and test its

Figure 7.19: A rendering of the Foster + Partners' completed dome-shaped habitat (Source: Foster + Partners).

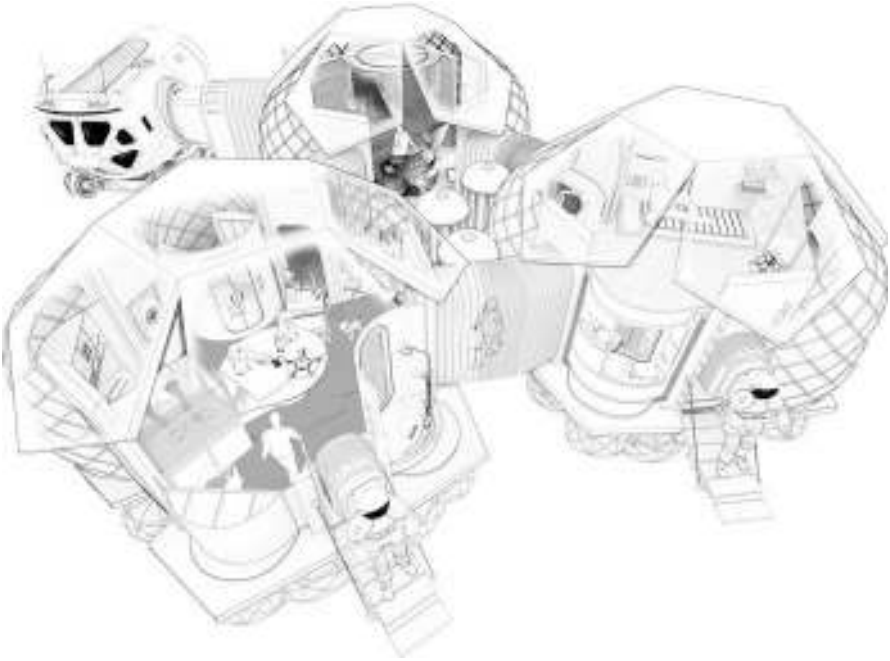

Figure 7.20: Axonometric drawing of the Foster + Partners' habitats (source: Foster + Partners).

Figure 7.21: Section drawing of the Foster + Partners' habitats (source: Foster + Partners).

Figure 7.22: Rendering of interior laboratory of Foster + Partners habitat (source: Foster + Partners).

functionality while scientists measure their health and wellness (D'Angelo 2021).

While the previous two designs both heavily utilize 3D printing and additive manufacturing, the unique partnership of ICON and BIG puts robotics at the very center of the stage. The same layering process introduced earlier is utilized here, though the raw material is ICON's proprietary concrete mixture that is apparently analogous to that which can be derived from Martian regolith (see Figure 7.25). ICON calls their Portland Cement-based mix Lavacrete, and it even features the texture and color of Martian regolith (Holder 2021).

Figure 7.23: Inside the Johnson Space Center, several vertical feet of Mars Dune Alpha are complete in this photograph – note the Vulcan II 3D printer in the background (source: BIG and ICON).

Figure 7.24: A rendered view inside of the Johnson Space Center depicting the Vulcan II (on the right) continuing to construct Mars Dune Alpha (source: BIG and ICON).

BIG and ICON imagine that the Mars Dune Alpha will sit on the Martian surface – quite different from the previous two designs that submerged living quarters. The design uses 3D printing to create a rigid shell structure that would protect inhabitants from radiation and micrometeors (see Figure 7.26). Using a rectilinear form also differentiates this design from the ZA Architects and Foster + Partners designs. The benefits of curved structures are eschewed

Figure 7.25: ICON's 3D printer the Vulcan II creating walls on the Mars Dune Alpha using a layering technique and a red-hued Portland-cement mix they call Lavacrete (source: BIG and ICON).

Figure 7.26: Rendering of exterior of Mars Dune Alpha; note the Vulcan II on the left side of the image constructing a second habitat (source: BIG and ICON).

by BIG and ICON in favor of a more conventional layout, though the domed roof is a nod to the heating efficiencies offered by a round shape.

The floor plan (see Figure 7.27) is conservative and hypersensitive to the economy of space – no square meter is wasted here. Not as evident in the plan view, Mars Dune Alpha will feature varying ceiling heights (accommodated by the domed roof) to avoid what BIG calls "spatial monotony," along with centralized and customizable lighting, sound, and temperature controls to "support the daily rhythm and well-being of the crew" (D'Angelo 2021). This explicit attention to psychological and mental health considerations is valuable, though the paucity of windows or access to sunlight undermines that objective. While not underground, astronauts living in Mars Dune Alpha may still feel like they are.

Figure 7.27: Floor plan of BIG and ICON's Mars Dune Alpha (source: BIG and ICON).

Zopherus

A team of relatively junior architects and designers[7] from Arkansas surprised the design world by winning one of the early NASA 3D printing competitions for Martian habitats. Their design envisioned a team of rovers equipped to extract regolith, process it, and then move to a construction site to 3D print structures. The mobile 3D printer concept received much enthusiasm, perhaps due to the fact that it captured a well-documented pattern in nature: "insects go out into the environment, find resources, process them into usable material, and construct the most practical habitat to meet their needs" (Torbet 2021).

With that insect model in mind, the Zopherus Team approached the form of their habitats with the same practicality: "The tough exterior shell of the Zopherus beetle, the tensile strength of a spider's web, and the hexagonal pattern of a bee's hive to create a modular footprint" (Zopherus Design 2021). This rigid shell structure sits on the Martian surface with no excavation required, and employs a dome shape (see Figures 7.28 and 7.29). The dome is covered with an outer lattice-like shell made from the 3D-printed regolith and an airtight inner layer made of High Density Polyethylene (HDPE), a petroleum-based plastic membrane that lets sunlight in and allows inhabitants to see outside (see Figure 7.30). The architects have not publicly shared information about an in-situ source for creating HDPE, though advances in membrane technology in combination with the ease of manufacturing glass make alternative local sources plausible.

[7] Trey Lane, Corey Guidry, Tyler McKee, Mark Hendel, and Austin Williams

Figure 7.28: Zopherus' proposal for a Martian habitat begins with a lander that functions as a 3D printing rover (source: Zopherus – Trey Lane, Corey Guidry, Tyler McKee, Mark Hendel, and Austin Williams).

Figure 7.29: A series of domed rigid shell huts comprising the Zopherus habitat sit in front of the 3D printing rover, now stationary (source: Zopherus – Trey Lane, Corey Guidry, Tyler McKee, Mark Hendel, and Austin Williams).

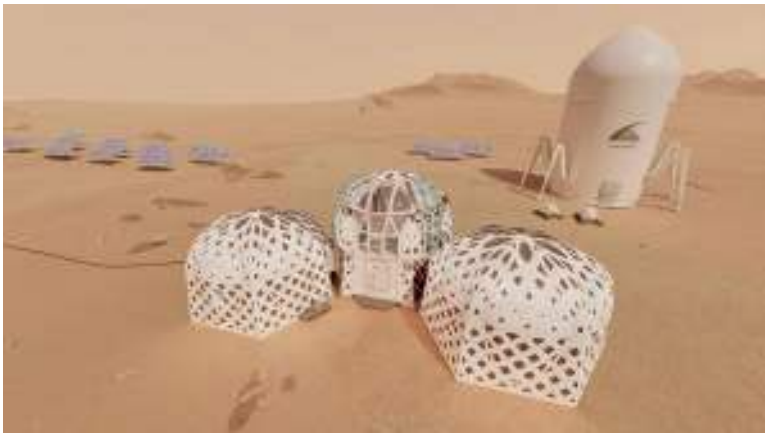

Figure 7.30: Aerial rendering of the Zopherus modular habitat units linked to a central, windowed hub unit (source: Zopherus – Trey Lane, Corey Guidry, Tyler McKee, Mark Hendel, and Austin Williams).

The entire concept embraces modularity, where units are built and then connected to the existing system as needed. The concept revolves around a central greenhouse pod, with additional units available to attach on all sides (see Figures 7.29 and 7.30). The habitat units are each divided into three types of delineated spaces for sleeping, working (laboratory), and socializing (communal) (Torbet 2021). Zopherus's lead designer, Trey Lane, explained in an interview that it was important to segregate those three activities (and others could be added due to the modular nature of the design) so occupants could psychologically separate those functions and maintain sound mental health (Torbet 2021) (see Figure 7.31). The communal unit features elements particularly conducive to emotional well-being: a large window for Sun and views outside, and proximate access to plant life (one of the Cognitive Architecture principles discussed in Chapter 4) (see Figures 7.32 and 7.33). Of course, while these windows offer important psychological benefits, transparent windows and sunlight do create challenges around heat loss and radiation exposure, as discussed earlier in this book.

In closely examining these four designs, the science and engineering ideas reviewed earlier in the chapter have come alive. The different options illustrate the benefits and trade-offs of the different materials, building forms, and construction methods available to the Martian architect. The embracing of 3D printing in each example speaks partly to the general popularity of additive manufacturing, and partly to NASA's focus on 3D printing in its competitions and commissions. This automated 3D printing approach means that some materials and machines need to be brought from Earth. By bringing metals,

Figure 7.31: Interior rendering of the Zopherus sleeping quarters, with some windows and natural light (source: Zopherus – Trey Lane, Corey Guidry, Tyler McKee, Mark Hendel, and Austin Williams).

Figure 7.32: Interior rendering of the lower-level of the central Zopherus communal quarters, with generous natural light (source: Zopherus – Trey Lane, Corey Guidry, Tyler McKee, Mark Hendel, and Austin Williams).

Figure 7.33: Second-floor (mezzanine) interior rendering of the Zopherus communal quarters. The space is shared with plant life and benefits from expansive windows and sunlight (source: Zopherus – Trey Lane, Corey Guidry, Tyler McKee, Mark Hendel, and Austin Williams).

membranes, and resins, these early architects can build structures that protect people from radiation, keep them warm, and (in some cases) attend to their emotional wellbeing and mental health. In-situ resources are utilized in all of these examples, but not exclusively. As discussed earlier, for the first city on Mars, that might just be the compromise that works, and future industrialization of Mars can allow for future cities to be built fully from in-situ resources.

Conclusion

This chapter served an important function, demonstrating the kinds of materials, forms, and construction methods needed for Martian building. In reviewing the science and engineering state-of-the-art on these topics, along with examples of four contemporary designs for Martian buildings, I can now present principles that will inform the final design of Aleph.

Principles for Building Science, Design, and Engineering Dimensions

1. Some construction materials may need to be brought from Earth, like metals, fabrics, and membranes, but minimally manufactured regolith can produce remaining needed materials like bricks, ceramics, glass, and concrete;
2. Various modular building structures and forms will be needed for Aleph, but domes represent the ideal shape for reducing heat loss;
3. Construction accomplished remotely or by robot prior to human settlement will reduce potential human harm; thus, 3D printing methods ought to be utilized whenever possible;
4. Ample natural light and views from the interiors of buildings are a necessary consideration in building design.

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8

Infrastructure Dimensions

The previous chapters offered some useful insights and principles around the laying out of streets, the arrangement of buildings, and consideration of land uses. What was missing was a discussion of how people might eat, drink, and breathe. What use is a lovely bike path if the air is poisonous?

This chapter turns to those very basic questions of life support systems that can allow humans to live on Mars: water, food, and air, as well as the related topics of energy, heating, and waste. While transportation is technically a type of infrastructure (see Chapter 5), this chapter covers the remaining infrastructure topics that must be examined in advance of the overall plan for the first city on Mars in Chapter 11.

While the typical civil engineer might be passionate about trash disposal, most of us go about our daily lives completely oblivious to the systems in our communities that support our basic living functions. In the Global North, most households have running water, sanitary sewage systems, electricity, heating (and cooling) systems, and some form of trash and recycling services. Turn on the faucet and water miraculously appears, flush the toilet and your waste is gone, turn up the heat on your thermostat and you are warm. Behind this apparent magic are well-thought out, redundant, and integrated systems that support human settlements. While exceptions abound, cities from Tokyo to San Francisco, from Mexico City to Cairo have invested trillions of dollars in infrastructure over centuries to provide high quality living to many of their residents.[1]

[1] Those left out of the infrastructure net tend to live in less developed countries or in informal settlements known as slums, and they lack access to clean drinking water, electricity, heating, cooling, waste management, and food (Huchzermeyer 2011; Davis 2017).

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J. B. Hollander, *The First City on Mars: An Urban Planner's Guide to Settling the Red Planet*, Springer Praxis Books, https://doi.org/10.1007/978-3-031-07528-5_8

While these systems vary drastically from one city and one continent to another, some are exceedingly efficient. Some have reusable, semi-closed, and fully closed systems that can conserve resources for an extended period. In desert climates, water is so precious that desalination and reuse systems are common. In remote locales, energy is scarce and solar and wind systems power life support functions. In environmentally conscious places, the wastes of one human function become the raw materials of another in a semi-closed loop – called an "industrial ecology approach" (Veleva 2015; Hollander 2001). These kinds of semi-closed systems require new resources as inputs, but far less than a completely open system that demands a constant flow of energy and new materials.

A true closed system is rare on Earth, due to our abundance of water, air, food, and energy, but scientists have been experimenting with creating such closed biospheres for over 50 years, with much to show for it.[2] Seedhouse (2009) explains that "in-situ resource utilization (ISRU) will require the development of extraction technology and highly advanced life support systems which will recover most of the waste products from human activity" (p. 7).

The University of Arizona operates Biosphere 2, a closed loop experimentation station in Arizona, U.S. Some of the more significant early closed loop system tests ever conducted took place at Biosphere 2 in the 1990s. These experiments involved the reuse of waste products for human activities. Two architects of these experiments wrote about their efforts and the power of the closed loop (Nelson and Dempster 1996). They explain what a typical human needs in a single day:

- 855 g of food
- 4,577 g of water (for drinking and food preparation)
- 128.3 g of water in food
- 18,000 g of wash/flush water
- 804.6 g of oxygen

They also calculate what a typical human generates as outputs in a single day:

- 3,025.5 g of water in urine
- 406 g of metabolic water (vapor)
- 1,680 g perspiration water (vapor)
- 18,000 g of wash/flush water (which can then be cleaned and reused)
- 161.4 g of solids (feces, urine, sweat solids)

[2] Closed systems are quite prevalent in outer space, on both long-distance space voyages (like the Apollo missions to the Moon) and the International Space Station.

While humans do not provide quite enough output to be recycled and reused, we almost do. Hence, a focus on infrastructure that is well-planned, aims for a closed loop, and integrates all food, energy, water, and waste systems is essential.

Some physicists have surmised that for a large interstellar mission, a combination of photosynthesis as well as chemical reactions can supply water and breathable air within a closed loop system (Marin and Beluffi 2020). The trick is in the extraction process, and one such system helps illustrate the possibilities: the Gas Extractor. Figure 8.1 shows how this would work in practice. In the upper left corner of the diagram, we see Martian air with its 95% carbon dioxide, 2.7% nitrogen, and trace amounts of argon, pulled into a device that first extracts water, reduces carbon dioxide, and then extracts the remaining buffer gases (nitrogen, argon, and carbon dioxide). From the water extracted, the vast majority would be used for supporting human habitats (for hydration, washing, and cooking) and greenhouses (for plant hydration). From the reduced carbon dioxide, some would be diverted for fuel, while the remaining would be fed into a system for water electrolysis, resulting in hydrogen, which is looped back into the electrolysis, and oxygen, which is used for fuel and to supply breathable air in the habitats. Likewise, the nitrogen and argon buffer gas is pumped into the habitats (people cannot breathe oxygen alone; we need buffer gases in our air), and the remaining carbon dioxide is delivered to the greenhouses so the plants there can breathe.

While not a closed loop, this approach shows how extracting the almost limitless supply of Martian air and being conservative with all its constituent parts can serve most of the water, breathable air, and fuel needs of a human settlement. The Gas Extractor approach also helps us think about the need for redundancy – multiple modules and paths for providing infrastructure (Hauplik-Meusberger et al. 2016). In Figure 8.1, some key paths are doubled over, and they can be doubled over again and again. The framework for good infrastructure considers what might happen if one or more elements of a system fails.

Most Earth-based cities tend to leave food systems to individual or market forces and air supplies are generally neglected (with the exception of problems related to smog and air pollution). Nevertheless, all of the other life support systems needed on Mars have already been developed and tested for millennia here on Earth. Numerous variants on closed loop systems have been in place in locations across Earth and have supported two decades of human settlement in low-Earth orbit aboard the International Space Station (see Figure 8.2). This chapter culls the most important lessons from that history, draws on the latest science and engineering research, and describes key principles that ought to guide Martian urban development.

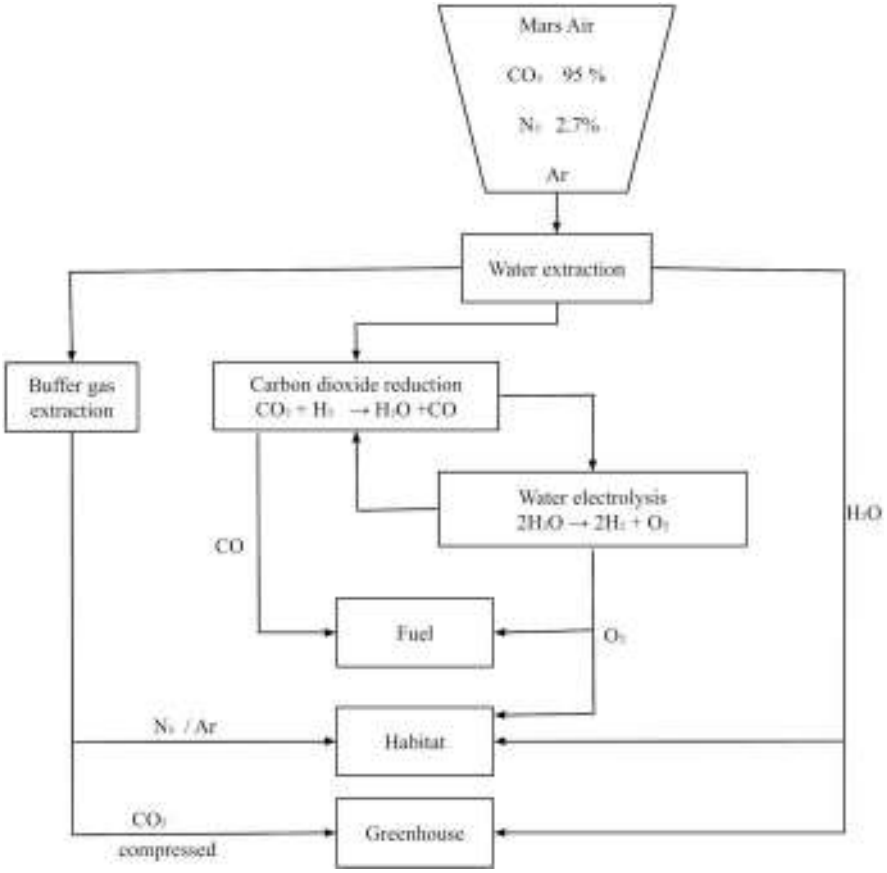

Figure 8.1: Gas extractor schematic (Elli Sol Strich, adapted from Nelson and Dempster 1996).

The Water We Drink (and Reuse)

The Bible says, "for you are dust, and to dust you shall return" (Genesis 3:19). In fact, humans are comprised of more than half of our weight in water. Without it, we quickly perish. This is a well-known fact in arid regions of Earth, where water is scarce. These arid and semi-arid zones cover around one-third of the surface of Earth. Yet, 15% of the planet's population live in these challenging environments and face a daily struggle to consume sufficient quantities of water (Mann 1986, p. 292). Overcoming water paucity is

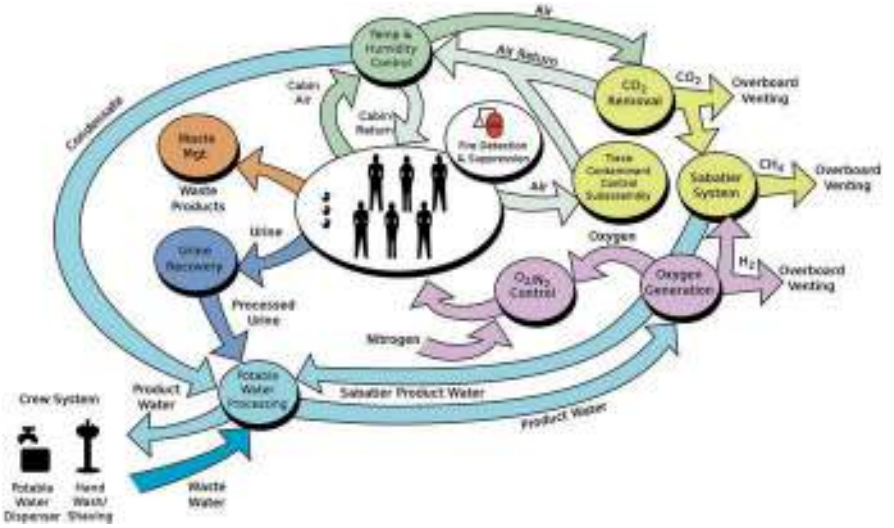

Figure 8.2: International Space Station closed loop (source: NASA).

something humans have done throughout history through creativity and ingenuity. We have built wells, canals, cisterns, and aqueducts. Today's modern city is nothing short of astounding in its ability to collect, store, and transport water.

Take Boston as an example. A state government agency, the Massachusetts Water Resources Agency, maintains a network of reservoirs up to 100 kilometers away from Boston, with elaborate pumping and piping that treats it, moves it, stores it in local facilities, and then distributes it to households and businesses throughout the region, providing 750 million liters of drinking water to 48 cities and towns (Massachusetts Water Resources Agency 2019).

Such a task is energy intensive and costly for Bostonians, but pales in comparison to what such a system looks like in an arid region like Arizona, U.S. The Phoenix Water Services Department provides 870 million liters of drinking water to its metropolitan area, largely through surface river supplies (Salt, Verde, and Colorado rivers), as well as groundwater reserves and reclaimed wastewater (not for drinking) (City of Phoenix 2019). Like Boston, Phoenix has developed a massive network of pipes, canals, treatment facilities, and storage facilities. But with evapotranspiration a threat and once-mighty rivers like the Colorado threatening to run dry, the region is in a persistent uphill battle to secure water resources.

Where regions like Boston have plenty of vegetation to hold moisture in the ground, arid regions like Phoenix struggle to keep the water they have in

liquid form. Likewise, dust pollution in arid regions can threaten to contaminate water supplies, a problem that wet regions like Boston do not face (Mann 1985, p. 292).

Urban planners the world over are accustomed to planning for water resources, creatively finding that water, then treating it, storing it, and delivering it to people. Providing water on Mars is just a bit trickier than the deserts of Phoenix or the Sahara or the Gobi, but not impossible. The first question most people ask is whether there is water on Mars at all. Luckily, scientists have known since the Viking Landings in the 1970s that water exists at quite abundant levels on the Red Planet (Petranek 2015). The reason this question continues to persist in our collective unconscious is because the presence of *liquid* water is more elusive. The available water is frozen solid in the planet's polar caps, embedded in regolith and a subsurface permafrost or aquifer layer, and trapped in the atmosphere (Meyer and McKay 1996; Boston 1996; Petranek 2015). Some experts speculate about the presence of subsurface water maybe a kilometer or more deep, where temperature levels could cause melting (Meyer and McKay 1996). Others argue that water could be reached by drilling as shallow as 10 to 20 meters (Impey 2019, p. 95).

For each source of water enumerated above, wild-eyed scientists and engineers have speculated about how humans might extract (jackhammers from the permafrost), withdraw (wells from the subsurface stores), or dehumidify (a water vapor absorption reactor from the atmosphere) this water (Petranek 2015). This is not a place to debate the best technology or most fantastic solution, just to offer that once obtained, water is "relatively easy to store and recycle" in a semi-closed loop (McKay 2007). Some have estimated that water vapor appears in the Martian atmosphere at 0.135% by volume, which would mean an extant supply of roughly 1.3 trillion liters (McKay 1985; Meyer and McKay 1996, p. 402). With water consumption for the average human estimated to be about 7,500 liters per year, that 1.3 trillion liters could last a city of 15,000 over a decade without any recycling. A semi-closed loop system, again relying only on atmospheric moisture, could provide water needs for hundreds of years (McKay 1985; Meyer and McKay 1996).

This semi-closed loop concept is also a well-known one on Earth. Many places, including the example of Phoenix mentioned earlier, regularly treat and recycle their water using "highly developed and readily available" technologies (Boston 1996, p. 337). Nelson and Dempster (1996) write about the opportunity to use aquatic plants and microbes to clean up animal and human wastes from flushed water. They discuss the concept of a "constructed marsh" where the plants and microbes do their work, resulting in fresh, clean, recycled water (Nelson and Dempster 1996, p. 373). These kinds of interventions

can recycle up to 3.32 kg/person per day of water, which exceeds the 2.57 kg/person per day of water that the average person needs (Nelson and Dempster, 1996, p. 411) (see Figure 8.2).

Likewise, the International Space Station has been recycling its water for over 20 years in a semi-closed system, whereby inputs of materials and supplies from Earth are regularly needed. Figure 8.2 illustrates conceptually how the ISS processes urine and condensed water to generate fresh potable water for astronauts. The water recovery component of the Environmental Control and Life Support System on the ISS appears as a stackable, integrated set of tubes, tanks, and machines (see Figure 8.3).

Once the water is obtained and purified on Mars, it needs to be stored in tanks to ensure long-term availability for the population. In addition, these tanks must be protected against puncture by numerous redundancy systems. With these steps, water can be a common resource on Mars, available to meet numerous human needs and recycled in a semi-closed loop to ensure availability for generations.

Figure 8.3: Water purification system on the International Space Station (source: NASA).

The Food We Eat

In Chapter 2, throughout the history of colonization on Earth, the cultivation, storage, and distribution of food always appeared to be on the minds of early planners. From laying out gardens and fields and setting aside space for grain storage and food markets in ancient times to today's zoning regulations that allow backyard chickens and community development programs that support community gardens, food has and always will be a central infrastructural element.

Just as water is a precious and rare resource in arid and semi-arid regions, food has been hard to come by for much of human history. Our ancestors spent most of their waking hours seeking it out, cultivating it, harvesting it, and processing it.

In many developed countries today, food abundance has created a new problem in widespread obesity (Hruby and Frank 2015). However, on much of the Earth, starvation and food scarcity are more common, and these societies have worked hard to create the kinds of communal and market-driven systems to ensure food access for all (Hossain 2017). For example, many places have restricted waterfront housing development to ensure fishing vessels have access to ports and fish processing facilities on the coast (see an overview of the Massachusetts Designated Port Area program in Heacock and Hollander 2011). The local food movement throughout many regions of the world has highlighted the benefits of consuming locally produced foods, while nations continue to maintain elaborate networks of global supply chains for providing off-season fruits and vegetables. Local, state, and federal planning initiatives have sought to put people close to these supermarkets to improve access to fresh and healthy foods, while other programs encourage food trucks to serve restaurant-quality meals to people where they are (Agyeman, Matthews, and Sobel 2017).

Depending on a country's political-economic system, food programs span everything from centralized cafeteria-provided meals to food stamps that subsidize low-income citizens. On Mars, the logistical challenges of extreme remoteness suggest Antarctica as a model for food system planning.

Very little food is produced locally in Antarctica. Instead, planes and boats bring in shipments of canned and frozen food that are strictly rationed (*National Geographic* 2019). The cold and windswept continent has been the site of experiments in growing plants in an environment not dissimilar to outer space, the Moon, or Mars (Wilhelm 2018). In a recent experiment, the European sponsored EDEN-ISI built a hydroponic greenhouse (san soil) and demonstrated the potential for growing food in a harsh climate, introducing cost-effective automation and monitoring equipment.

In the Biosphere 2 project introduced earlier, a team of scientists were confined to a series of connected rudimentary structures in a closed loop system in the Arizona desert. There, they consumed an average of 2,200 calories per day, including 73 g of protein and 32 g of fat, and experimented with over 3,000 species of plants, as well as many animals. Goats were the best "producers" among the animals (Nelson and Dempster 1996, p. 377). A Dutch study also looked at which plants might thrive on Mars and concluded that cress, tomatoes, rye, and carrots were the best performers (Petranek 2015).

Scientists aboard the ISS have conducted many agricultural studies to test the potential to grow food in space. Russians conducted 17 Rasteniya experiments between 2002–2011 using greenhouses on the ISS, demonstrating the viability of numerous plant species growth and in some cases favorable outcomes relative to Earth-based growing (Robinson and Costello 2018) (see Figures 8.4 and 8.5).

Shipping canned and frozen food to Mars is expensive. One estimate put the cost to send food to the International Space Station at $10,000 per pound (Wilhelm 2018). As such, most scientists recommend that Mars cultivate its own food, and given the cost and health benefits, to focus largely on a vegetarian diet. To do so would require an estimated 200 square meters of land or greenhouse space per person (Katayama 2008). Soil is a debatable question. One choice is to go hydroponic, like the experiment described above. Another option is to use the existing, in situ regolith, or rocky Martian soil, which some scientists believe can support plant growth (Wamelink et al. 2014; Nelson and Dempster 1996; Banin et al. 1988). An alternative is the use of

Figure 8.4: Cosmonaut Maxim Suraev with the Mizun lettuce plants from the Rasteniya experiment (source: NASA; Robinson and Costello 2018).

Figure 8.5: Detailed view of the Mizuna plant from the Rasteniya experiment (NASA; Robinson and Costello 2018).

smectite, a type of clay widely present on the Martian surface (as well as on Earth) that absorbs water easily and could be effective at growing plants with the addition of nutrients (Petranek 2015). Zubrin (1996) argues that Martian soil is actually "richer than that of Earth" (p. 195). He recommends planting mushrooms, beans, and fruit orchards (p. 196). He also suggests that fish farms, and tilapia in particular, could be a good food source on Mars because of their efficiency at converting "waste plant material into high-quality protein" (Zubrin 1996, p. 199).

A team of scientists from the German Aerospace Center (DLR) and the European Space Agency undertook an effort called the Micro-Ecological Life Support System Alternative (MELiSSA) to study a range of greenhouse solutions for permanent settlement on either the Moon or Mars. In a technical paper, they designed a hypothetical hybrid rigid-inflatable greenhouse, which with minimal energy and resource inputs and relying solely on existing technology, could provide food sustenance for six crew members for 24 days on the Moon (Zeidler et al. 2017).

The DLR team and other speculative ventures all include an input requirement of carbon dioxide, which is fortunately plentiful in the Martian atmosphere with only slight modifications (Nelson and Dempster 1996). Another challenge we have seen is radiation – not an issue farmers generally face on Earth. One option would be to bury greenhouses to reduce radiation exposure, but that would necessitate the use of artificial light through mirrors or fiber optics (Nelson and Dempster 1996). A better idea might be to develop crop strains that are radiation resistant (Nelson and Dempster 1996).

An alternative to ordinary plants for consumption would be single-cell proteins (SCP), microbes, algae, fungi, and yeast (Boston 1996; Kihlberg 1972; Goldberg 2013). Chefs today have done wonders with these creatures, turning them into gourmet meals and making them taste good. Given the many unknowns of plant growth, these SCPs may be a useful option for Martian planners to consider.

The planting and cultivation of fruits and vegetables may be more popular than harvesting fungi. People since antiquity have pursued some form of agriculture with great fervor as both a necessity and an as an avocation. Arguably, gardening provides people with "psychological sustenance" (Boston 1996) in addition to physical nourishment. More than 75% of Americans do some gardening, and it is considered to be one of the most popular hobbies in the world (Kaysen 2018). Whether for pleasure or not, growing food meets one of our most basic of human needs. Since we will not have the option of hunting or gathering on Mars, greenhouses with some degree of radiation protection, focusing largely on growing fruits and vegetables, should serve us well.

The Energy and Heat We Need

Walk around most of Manhattan in New York City and you will not see chimneys. You will not see oil tanks making deliveries either. Instead, the main source of heating and cooling for thousands of buildings in the country's biggest city is steam, generated centrally and distributed through an elaborate network of underground pipes. This system, the biggest in the world, is part of the invisible infrastructure that city planners and engineers conceive and lay out to ensure that human settlements have access to reliable heat and energy.

In Manhattan, the system is highly regarded and considered by many to be efficient and clean (Moyer 2017). Given the Island's extraordinary density of 27,000 people per square mile (NYC Planning 2019), compared to the average density of large U.S. cities at 283 people per square mile (University of Michigan Center for Center for Sustainable Systems 2020), such a centralized, planned system makes sense. In other locales, heating and cooling are highly decentralized. Bundles of wood are delivered for wood stoves, trucks bring heating oil and fill up basement tanks, or natural gas is routed to individual building furnaces.[3]

[3] Despite the widespread steam network, natural gas is an increasing source of heat for many newer and illegally constructed buildings in Manhattan (McGeehan and Flegenheimer 2015).

Factors that drive these questions around heating involve density (like the Manhattan example), but also access to heating sources and fuel. Remote settlements on Earth vary tremendously with regard to how they heat and cool buildings, with many equatorial locations (especially in the Global South) rarely doing either.

What is more universal on our planet is the need for electricity. Interestingly, sources of electricity also vary greatly from place to place. Centralized electrical networks are ubiquitous in the Global North, especially urban or suburban areas where electricity is plentiful and reliable (with the exception of the occasional storm-related power outage). Systems in the Global South also tend to be centralized, but not as reliable in urbanized areas. Rural areas tend to lack access to centralized, regular electrical service. Globally, the electricity that comes to a building, giving power to lights, computers, or kitchen equipment, can come from many sources: coal, natural gas, wind, solar, hydroelectric, nuclear, or the burning of trash (Ritchie 2014).

City planners have been increasingly involved in strategic thinking around these questions of heating, cooling, and energy sources and infrastructure. The regional planning agency that serves the Greater Boston area recently added a new Clean Energy division to its more conventional Transportation, Environment, Land Use, Municipal Collaboration, and Data Services divisions. Planners are integrating not just clean energy but all questions around energy into master plans for communities, altering zoning and other regulations to support distributed generation of electricity through rooftop solar and backyard wind turbines (GrowSolar 2019; Teschner and Alterman 2018).

In remote, arid, or otherwise Mars-like environments on Earth, delivering efficient and reliable electricity, heating, and cooling is a challenge. Scientists who have examined these questions have coalesced their thinking around several possible sources of power: solar, wind, methanol, and nuclear.

As on Earth, solar is a reasonable option for Mars, as it is a relatively simple and mature technology, offering scalable and flexible electricity for a remote settlement (NASA 2009; French 1985; Boston 1996). Estimates have put the solar potential on Mars, which only receives half the sunlight as Earth, at between 50 and 200 W per square meter (Haberle et al. 1993; Meyer and McKay 1996). There is one big concern for solar power on Mars: the collectors and related equipment are subject to dust contamination and coverage. On Earth, dust accumulation severely restricts the efficiency of solar arrays. Scientists have estimated that due to general ambient dust and dust storms, dust can accumulate at a rate of as much as 0.36 g/m^2/day in the Middle East. The dust devils prevalent in arid regions on Earth closely resemble the kind of dust storms that regularly blanket Mars, but at an inestimably smaller scale (see Figure 8.6).

Figure 8.6: Dust devil formation in the Mojave Desert (source: Jeff T. Alu / CC BY-SA 3.0).

NASA (2009) has written about this problem and proposes that autonomous dust mitigation technology could regularly fight dust accumulation on panels. Researchers have assessed this technology and generally conclude that such autonomous systems can be effective in reducing dust accumulation, though more technological improvements are needed (Mazumder et al. 2011; Alshehri et al. 2014).

Likewise, outdoor wind turbines would likely face challenging environmental conditions due to dust, though few options for screening or mitigating dust from wind turbines are available. In theory though, wind is attractive in that it could generate as much as 30 kW of electricity over an area of about 200 square meters (Meyer and McKay 1996; Haslach 1989).

Methanol is a controversial but potentially attractive option for energy generation on Mars (Nelson and Dempster 1996). Colloquially known as wood alcohol, methanol is widely used today on Earth in the manufacturing process of other common chemicals (Fiedler et al. 2005). Unlike other typical fuels on Earth, methanol can be stored as a liquid at Martian temperatures and atmospheric pressures. Environmentalists have called for the broader use on Earth of methanol due to its limited toxicity and safer disposal than other more common chemicals used for energy generation (Bertau et al. 2014).

Lastly, I turn to the much maligned but potent category of nuclear power. Commonly used on Earth, nuclear power represents a clean and plentiful, yet highly stigmatized power source. It can be a major source of electricity on Mars, also generating heat on those cold Martian nights. Dangers related to nuclear disasters and general radiation exposure are minimal, but perceptions of these risks are far greater (Gargaro 2018). It is worth noting that fuel cycle and decommissioning problems remain and would likewise be a challenge for Martian colonization.

On Mars, nuclear reactors could be buried underground and placed far from settlements, ideally at least one kilometer away, according to NASA (2009). Nuclear power is attractive because nuclear fuel is relatively light and makes travel and transport easier. Just about every NASA space mission has used some form of nuclear energy to power its remote and risky endeavors, including the first Moon landers, which used a 40 k We system (Newhall 2015; NASA 2009).[4]

NASA has been developing its Fission Surface Power System (FSPS) since those first Moon landings, experimenting with both nuclear and non-nuclear versions. Generating in situ fuel for these systems is challenging, but further exploration of the Martian landscape could reveal whether long-term nuclear power is a good option. Either way, nuclear can be part of a range of energy sources in a future Mars city.

Trash

Today, humans are faced with difficulties managing two types of trash: the kind that comes from our bodies (urine and feces), and the kind that emanates from our consumption and use of goods, packaging, and other material objects. These two types of trash are quite different, and urban planners struggle with them in unique ways. The sections on The Water We Drink and The Food We Eat introduced some of the key challenges of feeding humans on Mars, citing the value of our own waste as a source of raw materials for water and fertilizer.

Conventionally, we have used two systems on Earth to deal with human waste through indoor plumbing or outhouse technologies: sanitary sewers or septic systems. Sewers are piped systems that collect waste from toilets through an urbanized area, bring it together in centralized waste treatment facilities, then release solid waste (usually in hardened pellets to select manufacturing

[4] Many of these NASA nuclear systems have served as battery energy sources, whereas their potential for primary power sources on Mars is largely unknown.

uses) and liquid waste (usually as non-potable water sources for industrial activities). Planners have been perfecting the management and disposal of human waste for millennia, and we can expect similar systems on Mars, with increased emphasis on reuse and recycling, particularly using processed human and animal feces as a plant fertilizer (Nelson and Dempster 1996; Banin et al. 1988).

Here on Earth, there is growing interest in reducing waste and increasing human efficiency by recycling and reusing more than the typical paper, plastic, and metals. Some of these programs have taken aim at food waste, creating either closed loop food-waste systems or nearly closed loop systems. Concerns around climate change, the decreasing supply of fresh drinking water, and the increasing volumes of trash, have created a zero-waste movement. In the Dorchester neighborhood of Boston, a worker-owned cooperative Energy, Recycling, & Organics (CERO) is doing just that by collecting, composting, and selling food waste (Loh and Shear 2015). Cities like San Francisco have citywide curbside compost collection programs. Globally, numerous other local governments maintain more limited composting programs to collect food and garden waste, like Mirpur, Dhaka, Bangladesh, Johannesburg, South Africa, and Atizapán de Zaragoza, Mexico (Zurbrügg et al. 2005; Sehlabi 2012; Plasencia-Vélez, González-Pérez, and Franco-García 2018; Daigneau 2016). The industrial ecology movement described earlier in the chapter builds in mechanisms for this kind of waste recycling.

It is worth noting that paper, plastic, and metal recycling programs have spread drastically in the prior decades and provide for municipal and state reductions in household and business waste – provided that the recycled materials have a market value, which is something that has fluctuated greatly in recent years (Sound Resource Management Group 2019). When recycling is cost-effective, city planners have found that it diverts waste from landfills or incinerators. Landfills present an attractive option for waste disposal in areas with ample land supply, and incinerators can generate electricity through the burning of waste, making them an attractive option, if not for the resulting air pollution (Rabl 2008).

Even in the densest urban areas, trash collection has and continues to be a labor-intensive activity and generally involves motorized vehicles (typically trucks) that navigate all the streets of a city, collecting curbside bags of trash and recycling put out by households and businesses. In suburban and rural areas, residents may be asked to haul their own trash to trash transfer facilities or centralized garbage dumps.

Of all the infrastructure introduced in this book, our history on Earth of dealing with trash has got to be the poorest performer. Between the inefficiency, the odors, the noise, and the pollution of collecting trash, as well as the

wastefulness, pollution, and unpleasant aesthetics of disposing it, it does not seem sensible that Earth is where we should look for lessons on dealing with waste on Mars. If there is a principle for Martian planning hidden here, it is around designing waste collection, processing, and disposal systems to emphasize reuse and recycling, focusing on zero-waste (if possible), and to also try to prevent the generation of waste by encouraging or even requiring more thoughtful approaches to packaging and consumption to reduce the amount of materials going into the waste stream in the first place (Hauplik-Meusburger et al., 2016). This has been a goal of environmentalists for many years, and progress throughout the globe suggests such a framework could well be developed as the foundation for the design of the first city on Mars (McDonough and Braungart 2010).

Infrastructure Principles

Across air, water, food, energy, and trash, human settlements on Earth strive to be well-planned to meet people's most basic needs. As this chapter illustrates, not all places across the globe have equally provided services. In Bozeman, Montana, U.S., the air is fresh and plentiful; in Beijing, China, smog makes outdoor activities forbidden for children and the elderly. In Geneva, Switzerland, you will notice that the government-piped water is clean and pure, while regular wastewater treatment facility failures upstream make the Tijuana, Mexico water sometimes too hazardous to imbibe. Across each of these infrastructure categories, we have learned on Earth the right way and the wrong way to provide services, particularly in challenging, remote, and arid environments.

The following infrastructure principles will serve as a guide for planning the Martian city of Aleph:

1. Water can be collected from the Martian atmosphere, effectively stored, and reused in a manner to reduce evapotranspiration;
2. Infrastructure should be flexible and open to expansion over time, designed and built around reusing and recycling precious natural resources;
3. Supply and return infrastructure for industrial and commercial functions should be separated to avoid cross-contamination;
4. Food can be grown primarily from plants and single-cell proteins (SCPs) in a mix of aboveground greenhouses and belowground hydroponic facilities;
5. Heat and electricity can be generated from nuclear, solar, and methanol through the use of redundant and autonomous cleaning and repair systems whenever possible;

6. Nuclear reactors can be employed to regulate the temperature of Aleph, where sunlight can be directed into the settlement as a supplemental heating source;
7. Recycling and reuse facilities should be employed for managing waste to ensure that finite resources (materials, food, water, energy) are conserved as much as possible.

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9

Precedents

Since ancient people first peered into the night sky, human beings have always wondered about that red shimmering dot above them. By the late 19th century, astronomy had progressed enough to generate powerful imagery of the surface of Mars and the perplexing canal-like features crisscrossing the planet.

Few could have imagined travelling to such a distant and mysterious location. But the dawn of the Space Age changed all that. With men landing on the Moon (1969) and the Viking program (1975–1983) sending multiple probes and landers onto the Martian surface, suddenly the notion of a long-term human presence off-Earth seemed possible.

Ray Bradbury's (1950) acclaimed *Martian Chronicles* predated the Space Age, but quickly followed the end of World War Two and the twin nuclear bombings of Japan. Bradbury's vision of Mars did not benefit from the findings from the Viking explorations and reflected more the speculations of 19th century astronomers and fantasy writers. His poetic description of Martian cities served as a basis for much of the popular culture and science fiction that followed.

In this chapter, I begin with the *Martian Chronicles* and proceed with a sweeping account of how Martian cities have been depicted in fictional works, as well as other non-fiction efforts like my own. Some are by renowned space architects, some by established designers, and others by novelists. The aim of this chapter is to provide an overview of the range of plans devised and an analysis of each, ending with some conclusions about which elements of these plans have the strongest basis in the science, engineering, and city planning knowledge introduced in the previous chapters. These conclusions will be followed in Chapter 10 by a similar exercise in reviewing such precedents for space urbanism in other Off-Earth locations besides Mars, including the Moon, low-Earth orbit, and beyond.

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J. B. Hollander, *The First City on Mars: An Urban Planner's Guide to Settling the Red Planet*, Springer Praxis Books, https://doi.org/10.1007/978-3-031-07528-5_9

Bradbury's View of Martian Cities

Many early astronomers believed that water was plentiful on Mars. In the late 19th century, Giovanni Virginio Schiaparelli declared that the planet was covered in oceans not unlike those on Earth (Weintraub 2018). Schiaparelli used telescopes (which today are considered of quite low resolution) to map a network of lines on the Martian surface that appeared to be channels, or *canali* in Italian. Following the mistranslation of *canali* into English as "canals," astronomers for decades continued to observe and confirm the presence of this elaborate network of "constructed" waterworks (Johnson 2020).

One such 19th to 20th century astronomer was Percival Lowell, who went even further, reproducing Schiaparelli's "canal" maps with his own notations and conclusions. He widely promoted the notion of an elaborate system of constructed canals, stating that "the amazing blue network on Mars hints that one planet besides our own is actually inhabited now" (Hoyt 1976, as quoted in Weintraub 2018, p. 100). For two decades, Lowell collected observations to support this idea and published widely in the scientific and popular press to promote the notion of an advanced alien civilization.

> It is worth noting that Lowell's success in generating excitement about a canal-building alien population on Mars coincided with a time of great canal-building on Earth: the Suez Canal was built in 1869 and the Panama Canal was begun in 1881. Yet, with Mariner 4's Mars flyby in 1964, all hopes of a canal-building civilization crumbled. It appeared that Schiaparelli's original channels were simply point features (like large rock formations or depressions) that from far away appeared to connect to one another and create a line (Johnson 2020).

It is understandable that a writer like Ray Bradbury would be affected by those conclusions. Born in Illinois, USA in 1920, Bradbury became a renowned writer who focused most of his energies on science fiction. When the *Martian Chronicles* began to be released in serial publications in 1946, the world was at war, and Mars represented an escape for his legions of readers. The short stories were later compiled as a single book and published in 1950, when the memory of Hiroshima and Nagasaki was fresh and the capacity of humans to wreck this planet seemed all too real.

In the *Martian Chronicles,* Bradbury is not hopeful about Mars serving as a refuge, instead expecting humans to rush back home once war breaks out on Earth again. But his rich and vivid description of Martian cities is useful to explore here. Schiaparelli's canals are a major geographic feature in his story. His Martian cities largely appear as futuristic Earth cities, with tall shiny

buildings, plentiful open space and park land, and cozy, comfortable homes. Except for one short story where the Martians devise a scheme to murder the human astronauts by recreating the model of a small town in Ohio (either telepathically, physically, or a combination of both), replete with charming bungalow homes, white picket fences, and narrow lanes, most of the architecture and city planning on Bradbury's Mars is fantastical and otherworldly.

In *The Martian Chronicles*, after successive failed attempts at colonization, human do eventually settle Mars, though Bradbury's description of Earthlings' contribution to the Martian built environment is thin. It seems they mainly took over the cities abandoned by the Martians, who were almost entirely wiped out by diseases brought by the humans from Earth – an ode to the colonization legacy of Europeans in the Americas. Whatever new contribution these future colonizers made to shaping the built environment of Mars was prosaic and not notable enough for Bradbury to highlight.

Prairie View A&M University

Among the multitude of scientific reports on space exploration and colonization, a rather obscure study commissioned by NASA and produced by students and faculty in the College of Engineering & Architecture at Prairie View A&M University in 1991 stands out. Written with the explicit aim of designing a habitat for 20 astronauts to live permanently on Mars, the authors sketch out two diagrams for not just small habitats, but also a larger and more complex settlement that can accommodate thousands of people.

For the first concept, the Prairie View team began by siting what they called Lavapolis near the Martian equator, arguing that such a spot makes access from low Mars orbit economical, "simplifies rendezvous maneuvers," and is also proximate to the most important geological features of Mars – Olympus Mons and Valles Marinaris (Ayers, et al. 1991, p. 253). Specifically, they chose a two-kilometer-wide channel created by an impact crater at the base of Ceraunius Tholus, a volcano at 24 degrees N, 97 degrees W (see Figure 1.1).

The Prairie View team chose to build their habitat in lava tubes – tunnels that were created in ancient times when lava once flowed through them and emptied out, leaving intact a series of stable basalt rock tunnels belowground. This underground locale offers radiation shielding and helps to regulate temperature, avoiding the extremes of day and night on the Martian surface. The basalt rock can be mined to construct large glass panels that can help expand the settlement and allow for landscaping.

The second concept is even more compelling. Hexamars employs "space-frame structure[s]" that begin with a central core and have additional modules radiating out – all partially buried below the surface (p. 254). The team sited Hexamars at 3 degrees North latitude, 99 degrees East longitude right between Pavonis Mons and Ascraeus Mons, close to the equator, like Lavapolis. While the study authors spend little ink on the broader settlement requirements, they do enumerate key requirements of dining, entertainment, exercise, storage, living quarters, greenhouses, transportation bays to facilitate rover transport, oxygen storage facilities, and laboratories for a range of scientific experimentation and life support functions. Their central core and radiating and attached modules, all covered in domes, are clearly depicted in Figures 9.1, 9.2, and 9.3.

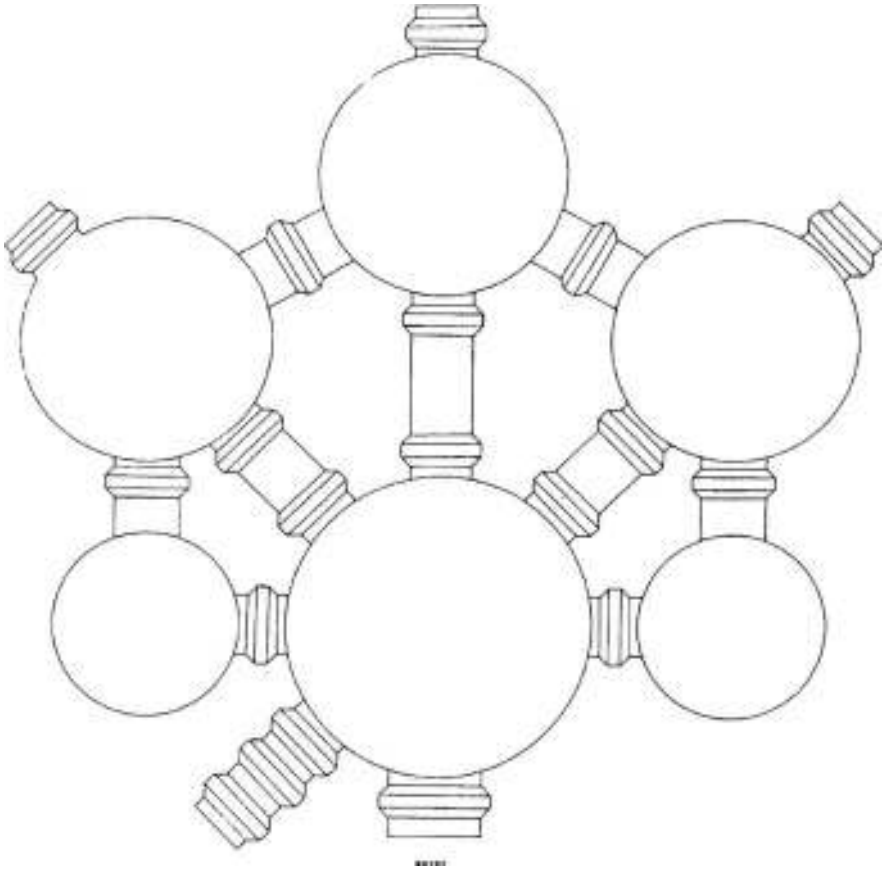

Figure 9.1: Roof plan for Prairie View's Hexamars design (source: Ayers et al. 1991).

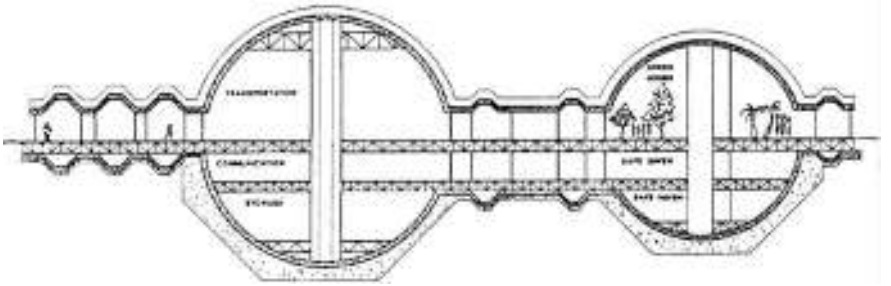

Figure 9.2: Section for Prairie View's Hexamars design (source: Ayers et al. 1991).

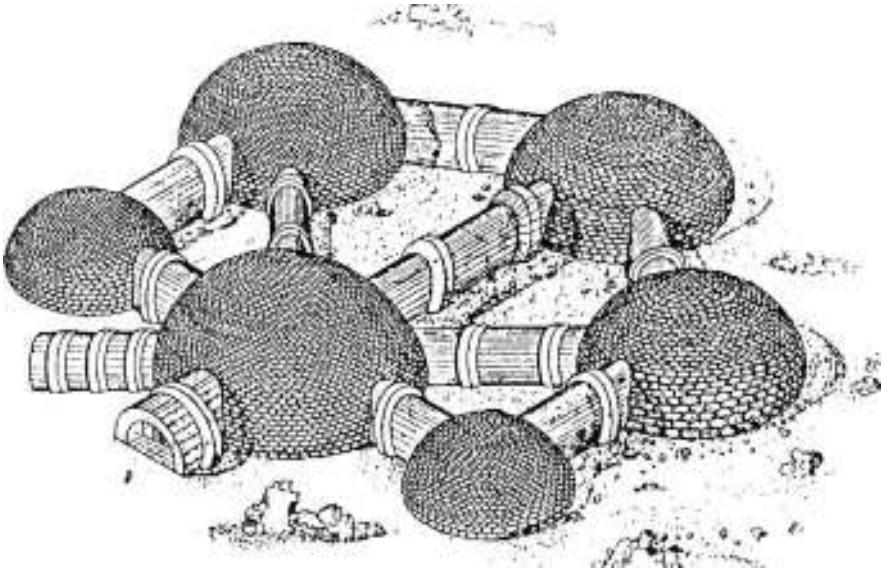

Figure 9.3: Isometric illustration for Prairie View's Hexamars design (source: Ayers et al. 1991).

The Hexamars design is quite familiar from science fiction depictions of Martian life, but the Prairie View team did a fine job of presenting a convincing case that this concept offers much with regard to efficiency, separation of activities, ease of construction, and modularity, which makes expansion simple. The construction of larger and larger nodes can accommodate increasingly larger populations in growing settlement, without compromising the elegance of the original design and early structures.

Zubrin's Mars Direct Plan

No scientist alive today is so closely connected in the popular imagination to Mars as Dr. Robert Zubrin. A former senior engineer at Lockheed Martin, former Chairman of the National Space Society, founder of the Mars Society, and author of seven books about Mars and space travel, Zubrin has had substantial influence in this area. Beginning with his landmark *The Case for Mars: The Plan to Settle the Red Planet and Why We Must* (1996), coauthored with Richard Wagner, he has been refining his Mars Direct Plan to settle the Red Planet ever since. Where Prairie View's Hexamars was a concise and simple articulation of a Martian settlement design, Zubrin's work is sweeping and comprehensive. While there is much to dissect in Zubrin's work, here I will review the most salient aspects of his plan to colonize Mars, beginning with site selection and moving through infrastructure, urban design, and manufacturing ideas.

Zubrin's ideas differ from others reviewed in this chapter and even this very book in his focus on the technical and engineering tasks involved in getting people to Mars. A major element of that strategy involves the establishment of multiple bases on Mars, which would be established for the purposes of analyzing soil, atmospheric, and other conditions for sustaining human life. After 10 years of implementation, Zubrin (1996) calls for the selection of the single base, which has the best conditions to be the site of the first human colonization effort (p. 14). That site would include some form of "geothermally heated subsurface reservoir" for the purposes of supplying heat and electricity to settlers and would be in proximate location to a water source (p. 15). He is particularly keen on a site in the Northern Hemisphere of the planet, pointing to evidence that water in most likely found there and that it is less impacted by dust storms (p. 129).

Zubrin envisions people getting around on Mars largely through specialized nuclear-powered flying vehicles and Mars Cars (a prototype developed by the Navy in the 1920s). These Mars Cars have a unique methane/oxygen fuel source diluted with carbon dioxide that fuels an internal combustion engine (p. 146). They also emit water but have built-in condensers that capture that water and reuse it back on base.

The use of the waste of one element as the raw material for another – a model of industrial ecology discussed in Chapter 8 – is a major organizing principle for Zubrin's plan. He writes about how Mars "is endowed with all the resources needed to support not only life but actual development of a technological civilization" (Zubrin 1996, p. 52). As such, he proposes a range of quite impressive manufacturing functions (like the ability to produce brick, plastics, steel, aluminum, silicon, and copper) that draw on each other's waste

streams and recycle and reuse those very resources, and as a result provide fuel, energy, and the water needed for the technological civilization of his dreams.

Regarding architecture, Zubrin's plan features subsurface Roman-style vaults and atriums, all constructed from brick manufactured in situ (p. 175). In addition, he proposed the development of a network of inflatable geodesic domes 50–100 meters in diameter that could serve a number of functions, including as greenhouses for agricultural purposes (p. 181 and p. 195) – though their radiation protective qualities are unknown.

Despite Zubrin's extraordinary attention to detail throughout his large corpus of writing, he pays little attention to urban design and planning consideration. For example, in his *Case for Mars* book, he includes just two spatial diagrams suggesting the arrangement of structures, their form or bulk, and the morphology of any surface (or subsurface) transportation networks. The first depicts an early Mars base, suggestive of the first six months or so after landing, and the second depicts what Zubrin calls a "mature base" that appears to accommodate several dozen residents at most.[1] Neither are substantial enough in size to effectively communicate any particular vision for urban form, beyond a somewhat tight cluster of domes and subsurface structures, mixed with a radio tower of sorts and surface roads extending in the cardinal directions for apparent exploration of Mars.

Mars Foundation's Mars Homestead Project

Few groups on Earth have been more focused on colonizing Mars than the Mars Society, a membership organization that has sponsored numerous conferences and publications since it was founded by Dr. Zubrin in 1997. More recently, the former Executive Director of the Mars Society, Bruce Mackenzie, led the creation of a competing nonprofit organization, the Mars Foundation. The Mars Foundation has made quite an impact itself with its Mars Homestead Project. As with the prior sections of this chapter, I will provide a concise overview of the Homestead Project and its site planning and design elements.

In contrast to Dr. Zubrin's work, Mackenzie and his team are not waiting to get to Mars and settle in for a decade before choosing a location to build.

[1] As with most Mars enthusiasts, and especially scientists and engineers like Zubrin, the grand challenge for them is just getting to Mars and, hopefully, surviving for a few years. This perspective differs drastically with the central premise of this book, where I embrace a much longer time horizon, imagining what a city of hundreds or even thousands might look like on Mars. Therefore, it is hardly fair to expect Zubrin and his ilk to include such physical design considerations that I am attending to here. They just want to get us there!

Instead, they have picked a site from afar. That's kind of like moving into an unseen apartment when relocating from Sydney to New York. They chose the Candor Chasma Valles Marineris, located at 69.95 West × 6.36 South × −4.4 km (Fisher 2005) (see Figure 9.4 and Figure 1.1). Their site involves the establishment of a two-story settlement built into a hillside.

The Homestead design utilizes a linear layout to maximize "efficiency in transportation, infrastructure, safety, and expandability," drawing on inspiration from Le Corbusier and Arturo Soria y Mata (Petrov et al. 2005, p. 23).[2]

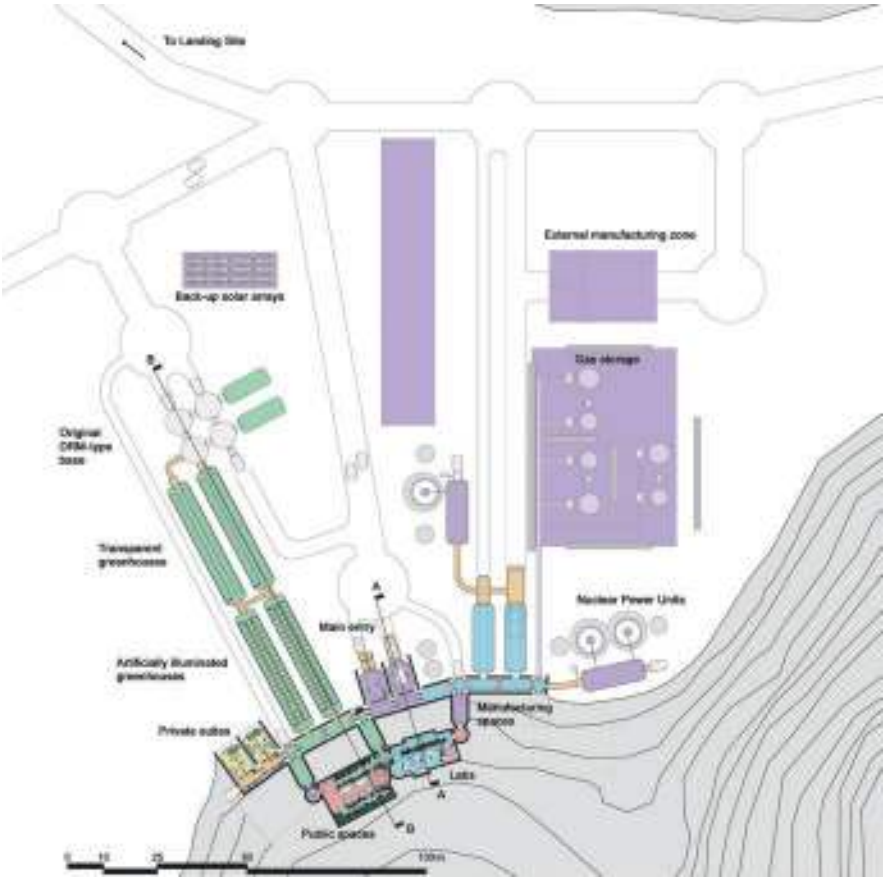

Figure 9.4: Plan view of the settlement located on the hillside of the Candor Chasma Valles Marineris (source: Georgi Petrov – Mars Foundation).

[2] Soria lived from 1844–1920 in Spain, pre-dating the Swiss Le Corbusier, who was born more than forty years later. Soria's "linear city" informs some of Le Corbusier's (1929) tendencies towards a rationalization of urban form and obsession with rectilinearity, or what he calls orthogonality.

While these linear cities were enormously popular in their day and for decades later, such rigid modern town planning is widely panned among contemporary practitioners and academics alike (Gehl 2010; Jacobs 1961; Ewing and Bartholomew 2013). It is worth noting that Saudi Arabia has developed a plan for such a linear city "The Line," to eventually extend over 160 km across arid deserts, linking the northwest mountains of the country to the Red Sea and housing one million people (Avery 2021). Given the similarities between the remote and dry Saudi deserts and Martian landscapes, this linear city plan offers some valuable lessons.

The Mars Homestead linear plan follows along where the edge of the hillside meets flat land. That edge is the spine that organizes the entire community, linking housing, work areas, and infrastructure/utilities. Public spaces are integrated into the interior hillside areas, thus shielding people from radiation and modulating extreme temperature fluctuations. Overall, the Homestead layout is fairly compact, like that of Zubrin's plan, with housing, work spaces, manufacturing, gas storage, and nuclear energy generation uses all in close proximity, allowing walking to be the primary means of internal city mobility (see Figures 9.5 and 9.6).

The plan calls for a spectacular investment in vegetation in order to express deep-seated human aspirations and needs. The plan's authors write that trees would be planted at the main entrance and spread throughout as the settlement grows, surrounding social spaces to provide protection and enclosure, as well as in a green belt of land surrounding work spaces (Petrov et al. 2005, p. 30) (see Figures 9.7, 9.8, and 9.9).

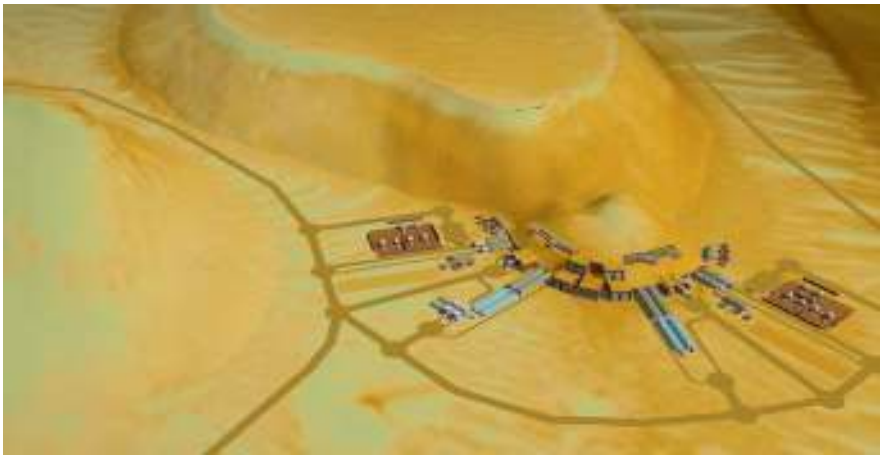

Figure 9.5: Exterior rendering of the Homestead layout (source: Georgi Petrov - Mars Foundation).

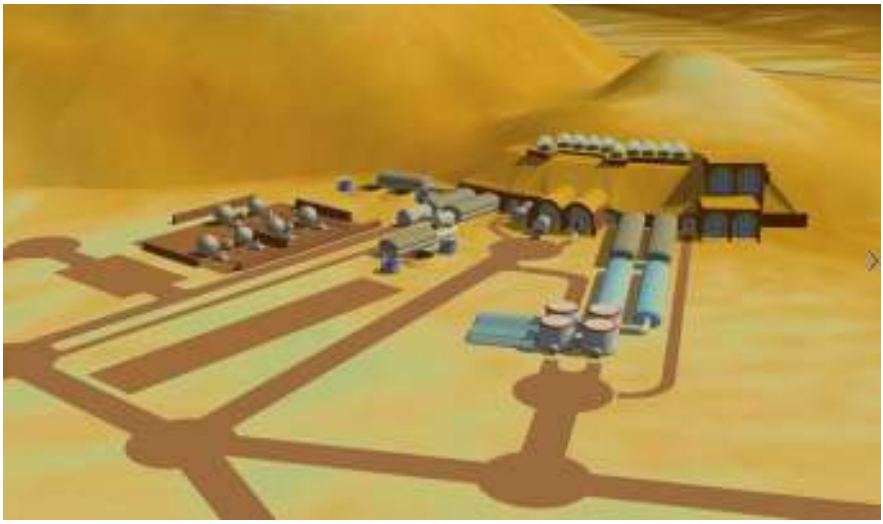

Figure 9.6: Exterior rendering of the Homestead layout, illustrating the close proximity between structures and the ability to walk for inner city circulation (source: Georgi Petrov - Mars Foundation).

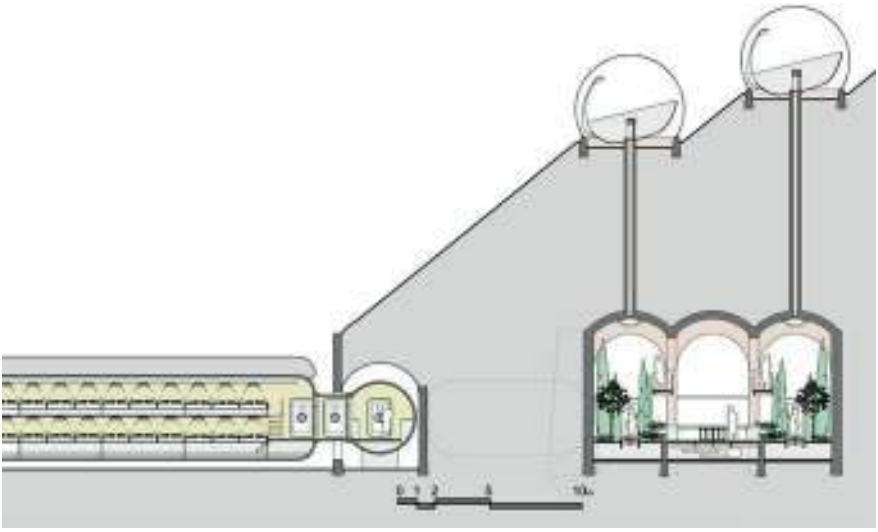

Figure 9.7: Section of a hillside structure, with public spaces in the interior hillside area (source: Georgi Petrov - Mars Foundation).

For building construction, the Mars Foundation team embraces masonry and plans to compress and sinter regolith and in situ stone (Petrov et al. 2005, p. 7). For the hillside structures, a range of arches, domes, and "pitched brick

Figure 9.8: Eye-level rendering of the Homestead Project (source: Georgi Petrov - Mars Foundation).

Figure 9.9: While no trees are visible in this sunset rendering of the Homestead Project, trees would ideally be located at the main entrance and surrounding social spaces. (source: Georgi Petrov – Mars Foundation).

vaults" would be accompanied by additional domes, inflatable structures, and arched structures covered with regolith outside the hillside (p. 9). The brick structures introduced in this plan were the ones that Zubrin largely embraced in his Mars Direct Plan and were the basis of the buildings described in Kim Stanley Robinson's *Red Mars* series, which I turn to next.

Red Mars

If Bradbury was using the setting of a future Mars civilization as a backdrop for his biting social criticism, Kim Stanley Robinson's ambitions in his 1992 *Red Mars* were more self-indulgent, using the novel to fantasize about what such a civilization might look like and how it might function – social critique notwithstanding. Where Bradbury employs the wit and imagination of a poet to paint his picture of Martian urbanization, Robinson uses the tools of the scientist and engineer to present a compelling vision of a settled Mars. Beginning with the depiction of the laborious trip from Earth aboard the spaceship Ares, Robinson shows the reader two distinct settlement plans: 1) Underhill, the early initial settlement for the first wave of colonists, and 2) Nicosia, a mature model for widespread urbanization of Mars. Throughout *Red Mars* and two subsequent novels, *Green Mars* and *Blue Mars*, Robinson describes numerous other settlements and cities, but few are given the attention to detail that these first two enjoy. The first book of the series, *Red Mars*, covers the first half-century of Martian colonization, a sufficiently long time horizon that matches the time scope of this book.

Before turning to a close review of the two settlement plans, it is worth noting that intra-settlement transportation was projected to be the same for both. Robinson writes of two major ground-based transport systems: small and large rovers. The small rovers accommodated up to two people and were designed for short ranges, while the large ones could handle much longer distances, additional passengers, and even included sleeping quarters. The network for these rovers was imagined as unpaved roads, where each rover was equipped with a snowplow or small crane on the front of the vehicle to clear rocks or other debris (Robinson 1992, p. 135).

Dirigibles provided aboveground transportation in Robinson's Martian world. Filled with hydrogen to help stay aloft and powered by solar cells and storage batteries, a fleet of these flyers allowed for long-distance travel between settlements and for scientific exploration (Robinson 1992, p. 180). Notably, Robinson never writes about any settlement or Martian city in *Red Mars* that is large enough that it cannot be traversed by foot, with rovers and dirigibles only needed for explorations beyond the settlement. In one of his cities, Senzeni Na, Robinson explicitly describes underground tubes for pedestrian circulation (Abbott 2016).

Underhill was located in Chryse Plantia in the planet's Northern Hemisphere, above the equator. This was seen by fictitious site planners as an attractive settlement location, especially as it was the site of real landings by

Viking and Pathfinder probes (see Figure 1.1). For the more advanced town of Nicosia, proximity to a space landing site was not as critical, and Tharsis, west of Noctis Labyrinthus, was chosen as a site location, near the equator with a view of Pavonis Mons (p. 4) (see Figure 1.1).

Given the climatic and radiation challenges of life on the surface of Mars, Robinson chose to embrace the brick, vaulted hillside structures proposed by the Mars Foundation and Zubrin. Affectionately referred to as Underhill, Robinson's habitats have no natural light and feel to the residents like mole-living – always just a necessary interim home until more elaborate above-ground housing is possible.

In Underhill, the vaults are arrayed in the shape of a square and connected by underground paths. The middle of the square contains "a central garden atrium of 10,000 square meters" (Robinson 1992, p. 161). Domes dot the Underhill landscape, made of thick, treated double-paned glass (p. 161). The entire settlement is arranged along a cardinal orthogonality, with roads extending east to a water manufacturing facility and north to spacepads (p. 181). A factory complex resembles a trailer park and sits somewhere in an outlying area beyond the settlement (p. 181).

Nicosia represents a drastic departure from the Underhill lifestyle. Built along a ridge, the town is shaped like a triangle, where the highest point is a

Figure 9.10: Pierre-Semard street in Paris, France (source: JLPC / CC BY-SA 3.0).

park. From this apex, "seven paths rayed down through the park to become wide, tree-lined, grassy boulevards" (Robinson 1992, p. 5). Between these boulevards, trapezoidal buildings sit neatly on the Martian surface, "faced with polished stone [each] of a different color" (p. 5). It is "an immense clear tent, supported by a nearly invisible frame" that makes this aboveground living possible (p. 4). With a startling level of scientific precision, Robinson describes the components, materials, and engineering that make this second-generation urban form possible on Mars. Like Pirsig (1974) in the *Zen and the Art of Motorcycle Maintenance*, Robinson savors the details in his vivid descriptions of enclosures that pressurize, heat, and protect inhabitants from the deadly Martian atmosphere. He goes on to draw a parallel with what some might argue is the most beautiful city on Earth: the "size and architecture of the buildings gave things a faintly Parisian look, Paris as seen by a drunk Fauvist in spring, sidewalk cafes and all" (p. 5–6). While Bradbury uses the literary equivalent of cartoons to depict the urban form of his Martian cities, Robinson embraces the Cognitive Architecture philosophy described in Chapter 3. Evoking the well-defined edge conditions, bilateral symmetry, hierarchy, face-like facades, and satisfying narrative of a traditional Parisian street (see Figure 9.10), Robinson creates a settlement that meets the needs of Earthlings far away from Earth.

Nicosia, Underhill, and other settlements described by Robinson feature much of the state-of-the-art food production (greenhouses where everything is recycled), energy generation (nuclear, solar, windmills), and water mining (robots bore for water and then automatically transport it to the settlements) that I have written about earlier. *Red Mars* presents a fictionalized version of much of what I present in this book through Chapters 5, 6, 7, and 8, drawing on some of the best science and engineering sources to show what is possible – without citing those sources and with the creative license afforded to a fiction writer.

Robinson was interviewed about city design and his Red Mars trilogy and said:

> …I recall in particular having the opportunity to design city after city in my Mars trilogy and enjoying that immensely. There I was often thinking about the ancient Greeks' placement of their cities on overlooks or in other locations with a fine view. Visiting the ruins of these places in the mid-1980s, I often felt the Greeks' locations were as much aesthetic as strategically defensive. They had beautiful prospects. And as I studied the new topographic maps of Mars generated by the Viking orbiter, I saw there would be many opportunities on Mars to build in similarly dramatic places, just for the pleasure of being there and looking around. (Daou and Gomez-Luque 2020, quoting Kim Stanley Robinson, p. 174)

Beyond the myriad of functional and practical elements of Robinson's designs for Martian settlements, his passion for creating aesthetically attractive places that would generate impressive views and give their occupants pleasure is quite striking. It is a sensibility in city design that is consistent with the science and psychology research presented in Chapter 4 and reinforces the importance of beauty, which is increasingly associated with architecture and design (Ruggles 2017; Burras 2020; Hollander and Sussman 2021). Robinson's message is compelling: creating cities is not enough – we should be creating beautiful cities that give people joy.

Joanna Kozicka and Her Dissertation

In 2008, Joanna Kozicka published her doctoral dissertation through the Faculty of Architecture at Gdańsk University of Technology, titled "Architectural problems of a Martian base design as a habitat in extreme conditions: Practical architectural guidelines to design a Martian base." She built on a longstanding research record that she and her husband, Janek Kozicka, a Polish engineer and academic, had built up over the previous decade. Joanna was not a typical PhD student: her research on Mars was nothing short of profound.

Through a search of the Proquest Dissertation database, I looked for all doctoral dissertations that have ever been published that included the terms Mars and architecture (or urban planning) in their abstracts. Nothing came up. I found Joanna's research through a scholarly journal article she and her husband published on one of the Mars base designs they came up with (Kozicka and Kozicka 2011). Most scholars are focusing their attention on more immediate and pressing research questions. Not Joanna and not me. For people like us, the long-term is exhilarating and requires present-day investments and policymaking. She channeled her passion into a 332-page thesis that does for Martian architecture what I am doing here in this book for city planning. She distilled the science and engineering lessons across a range of considerations (some of the same that I looked at, like life support and construction), but she also spent a lot of time considering building-specific topics that I have not been as focused on, like interior design, internal circulation, and air handling.[3]

[3] I was struck by the parallels in our overall organization, where after each section she concludes with "conclusions for architects," which include the kind of principles you are now familiar with in this book. Because of her focus on the building scale instead of the urban scale, her conclusions are quite different than mine but have informed my thinking throughout.

Kozicka reviews many individual building ideas that can handle a crew of 4–5 people. She also wrote about one small-town plan developed in 1990 that would be a permanent home to 150 people and can accommodate 150 visitors at a time. The plan, Mars Habitation 2057 (Dubbink 2001) by Obayashi Corporation in Japan (Kozicka 2008, p. 278), would be sited in a valley with hills on three sides for protection, with habitats drilled into the slopes of the hills (see Figures 9.11 and 9.12). The Mars Habitation 2057 design uses a ring-like dome system covered with protective ground layers.

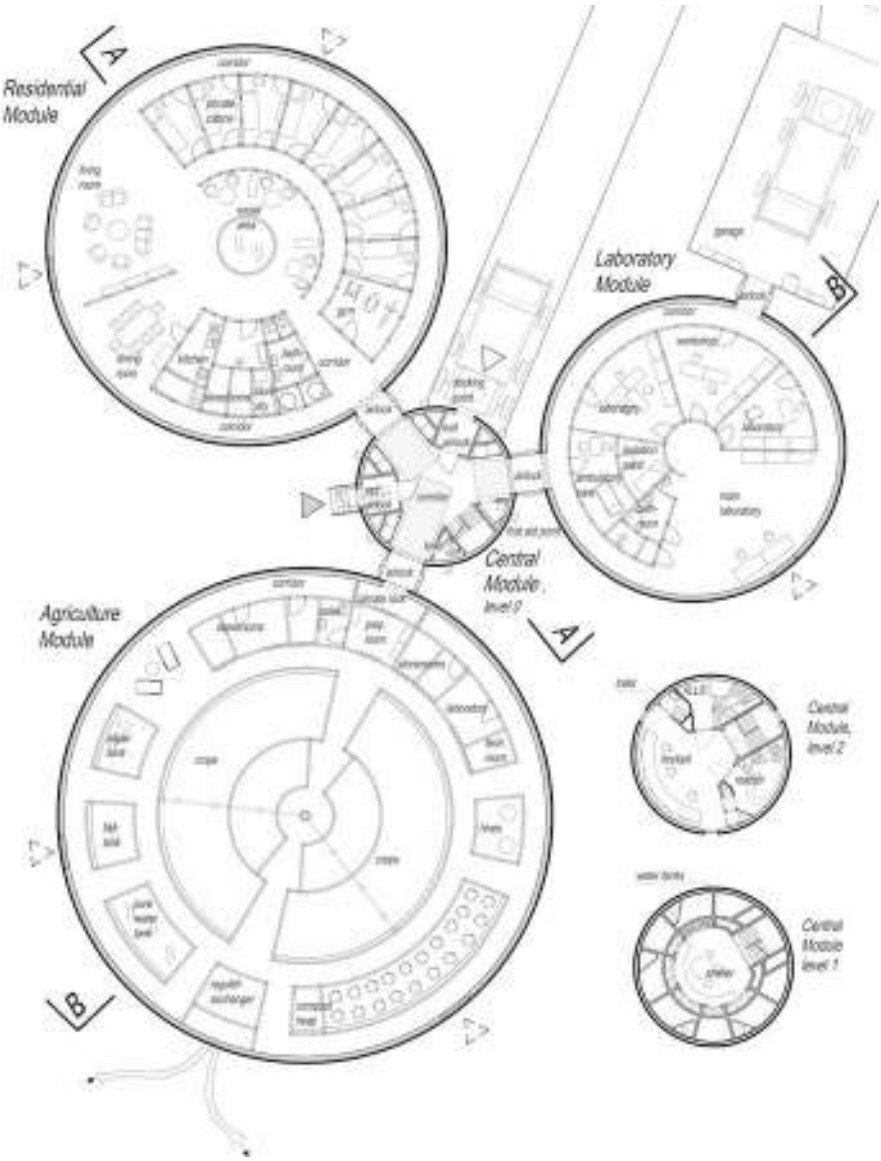

Figure 9.11: Plan view of the Mars Habitation 2057 (source: Kozicka 2008).

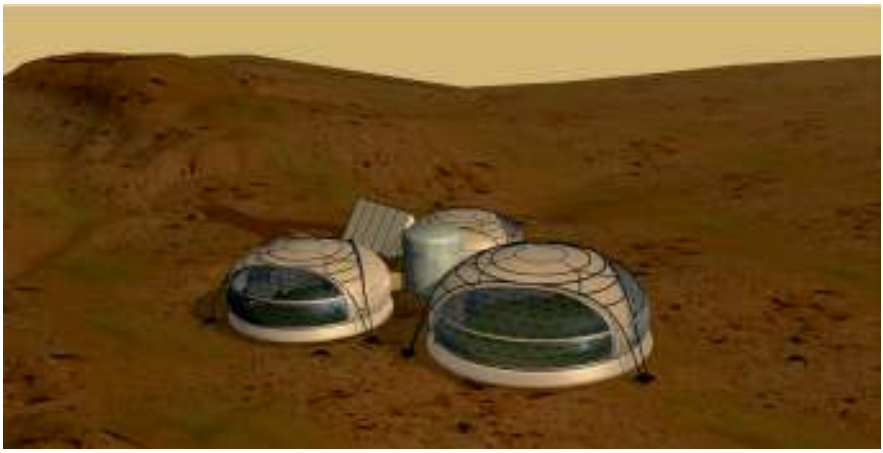

Figure 9.12: Exterior rendering of the Mars Habitation 2057 (source: Kozicka 2008).

Kozicka starts with the question of a building site. Rather than decide on an ideal location, she instead considers many architectonic solutions to building on the Martian landscape, considering building on plains, into a cliff, foothill, inside a hill, a crater, a valley, or "chaotic terrain" (p. 42). For each, she finds that a unique design solution could be found to build a structure, but concludes "that the safest base would be built on plains, due to an easy access of transport shuttles" (p. 44). She also stipulates that any building would need windows (or periscope windows) and natural light, should be covered with regolith, and should include multi-level construction.

Considering the varied terrain of Mars, Kozicka develops many well-illustrated design concepts, including four that demonstrate distinct approaches to site design and planning:

1. a chaotic one, where the arrangement of structures and the linking of underground passages respond directly to the irregular Martian landscape of hills and valleys
2. a network of small, interconnected domes cut into a slope on rock shelves
3. terraces on a slope, with all structures carved into rock
4. a mix of a central dome and underground tunnels (with skylights to let light in)

It is the fourth concept that stands out for me. Sited within an existing crater, a dome covers a central courtyard where plants are grown. The dome is further reinforced with a protective net (see Figures 9.13 and 9.14). Beyond agriculture, all human activities and living quarters occur in sheltered environments either within the excavated walls of the crater or underground. What is

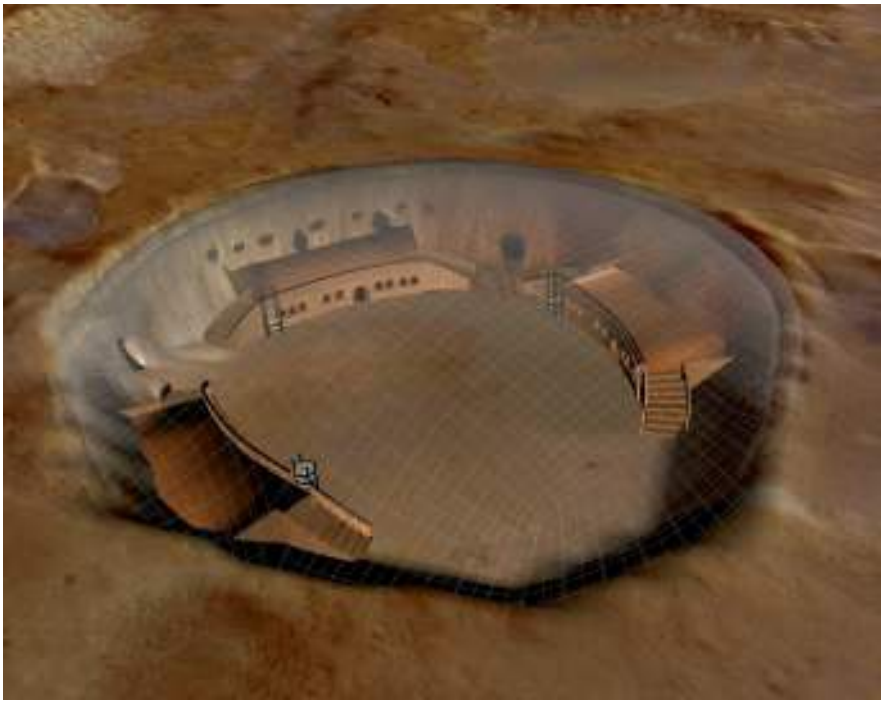

Figure 9.13: Rendering of Concept 2, with a dome situated in a crater, covered with protective netting (source: Kozicka 2008).

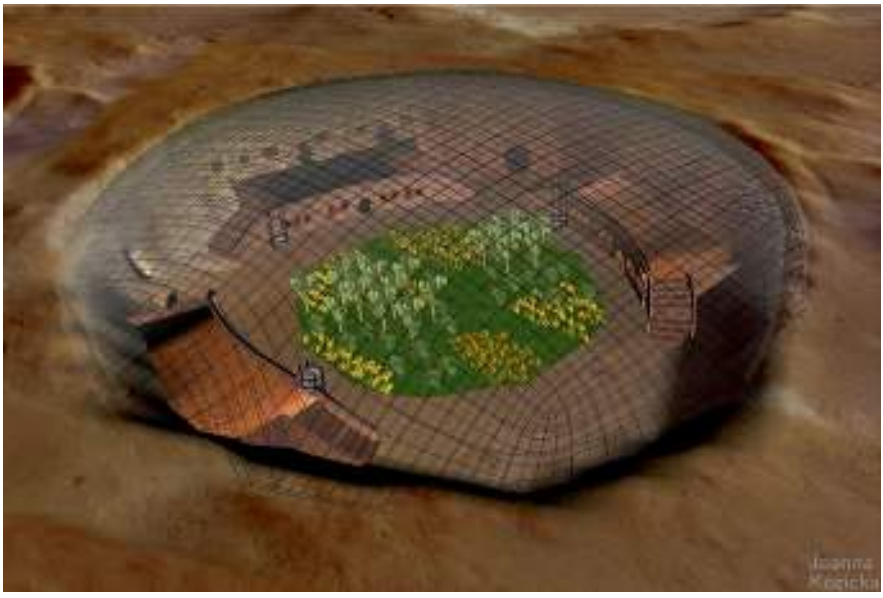

Figure 9.14: Rendering of Concept 2 illustrating plants growing in the central courtyard (source: Kozicka 2008).

attractive in this design is that it effectively solves many of the engineering challenges of maintaining life support systems, protecting people from radiation, and providing light into some living spaces. The design also provides for expansion and even envisions underground tunnels connecting two of these craters. This concept is highly scalable, since additional craters could be built into across the Martian landscape and each could be connected via tunnel to each other.

What is lacking in Concept 2 and much of the rest of Kozicka's dissertation are internal and external transportation considerations. This is reasonable given her scale of interest: the building. With the focus of this book at the broader urban scale, the need for additional transportation options beyond surface rovers becomes essential. Concept 2 could be readily expanded to incorporate a larger footprint and improved internal and external mobility options.

Austin Raimond's Master's Thesis

Quite a few Master's theses have looked at the question of how to plan for a city on Mars. Austin Raimond's stands out. Published relatively recently in 2016, Raimond's thesis is a compelling and rigorous application of architecture and planning history and knowledge to the question of Martian city planning.

Raimond developed a sophisticated rating system to evaluate a dozen possible locations for his settlement. He considered 27 suitability criteria, including solar exposure, likelihood of water, space for agriculture, access to views, and availability of construction material on site and ultimately selected Mosa Vallis (in Gusev Crater) for the site of his proposed settlement, specifically the North Crater (see Figure 9.15 and Figure 1.1).

Raimond developed a plan to accommodate 60 persons, an initial research team of 12 and a later settlement group of 48, projected to increase to approximately 100 within 10 years (Raimond 2016, p. 28). Due to the settlement's relatively small size, little attention is paid to internal transportation within the settlement, as it can be easily traversed by foot. External transportation beyond the settlement is also not heavily emphasized in Raimond's plan.

Regarding infrastructure, the plan considers a variety of potential heat and energy sources, including large solar fields at the edges of the settlement. But overall, it focuses primarily on the layout and design of structures. This is where the plan's greatest strength lies. Raimond begins by adopting the visual language of the rolling hills of the Gusev Crater region, while referencing the

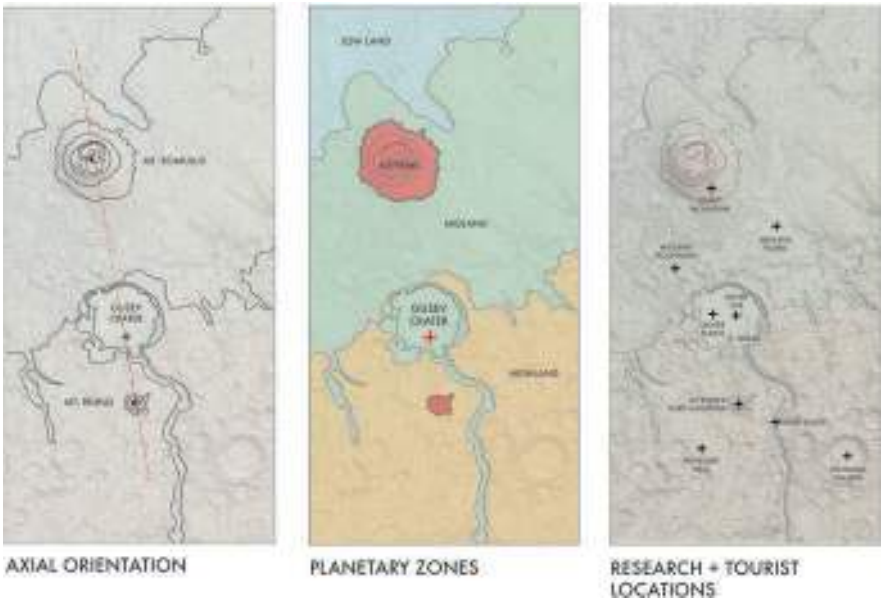

Figure 9.15: Regional context for Raimond's proposed settlement (source: Austin Raimond).

Figure 9.16: Ground-level view of Raimond's proposed settlement through an augmented reality visor displaying a computer interface (source: Austin Raimond).

hilly terrain of the Western U.S. and the romantic notions of westward expansion during the 19th century. He explains "settlers will be able to find comfort in knowing their dwelling is proportionally equivalent in visual size to the landscape surrounding it" (p. 46) (see Figure 9.16).

In Raimond's preliminary sketches for the settlement design, he draws inspiration from cliffside dwellings like those discussed in Chapter 6, where the heating and radiation protective qualities of a cliffside or rim of a crater can be carved out (see Figures 6.4 and 6.5). His basic plan in these sketches shows a central domed structure with four extensions emanating from each presumable cardinal direction at a 90-degree angle from one another. Along each leg of the settlement is a variety of independent uses: dwellings, communal spaces, vegetative, and hallways (for pedestrian circulation), are each segregated into unique zones, with roofs held up by arches.

The layout of the plan is grounded in some of the constraints recommended by the Law of the Indies (discussed in Chapter 3) regarding the overall orientation of the settlement and assignment of uses to various zones (see Figures 9.17, 9.18, and 9.19). Raimond explains that the:

> southern wing of the building includes a series of research laboratories, vehicle bay, and fabrication shop, all of which can double as both working and educational spaces within their respective disciplines. The northwestern extension is made up of a series of vertically sunken courtyard apartments, which serve as both the main living and food production spaces within the settlement. (p. 48)

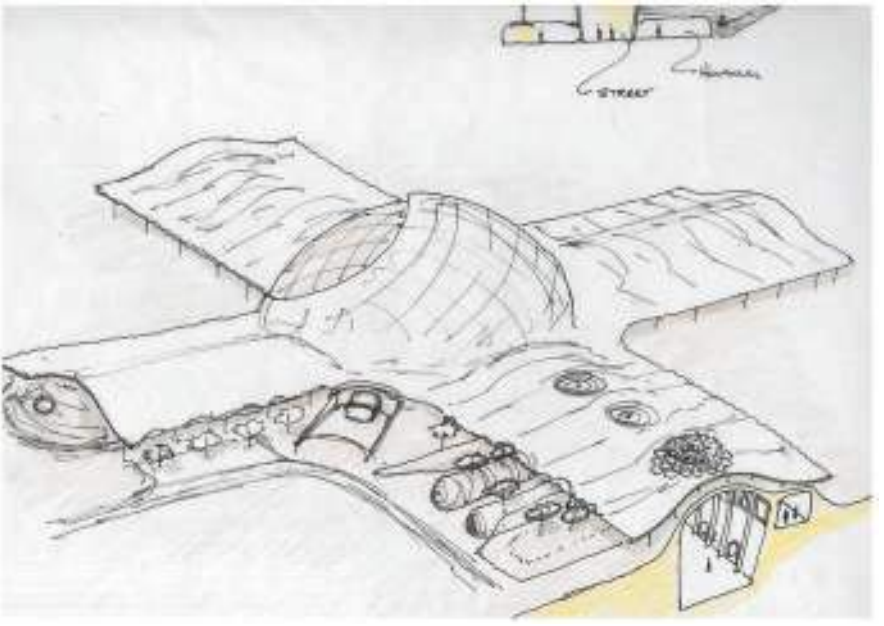

Figure 9.17: Early conceptual sketches of Raimond's proposed settlement (source: Austin Raimond).

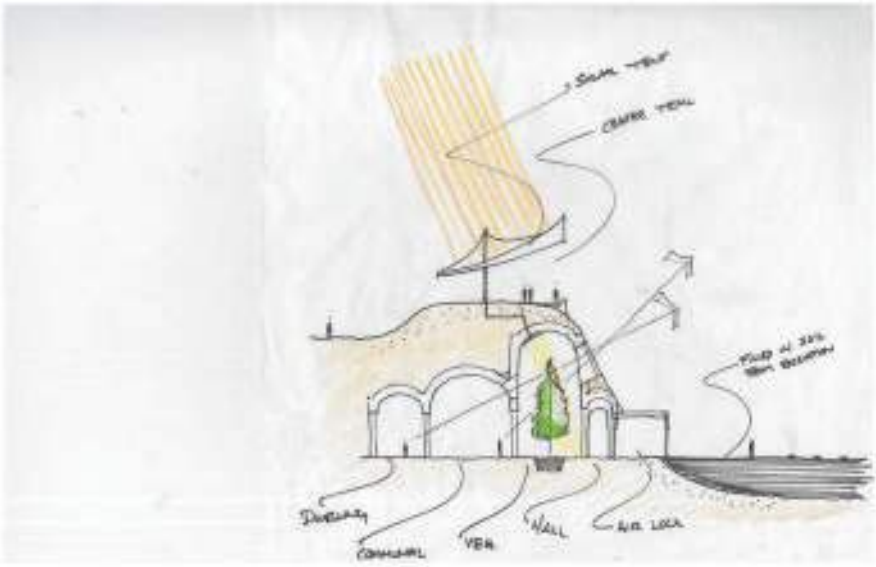

Figure 9.18: Early conceptual sketches of Raimond's proposed settlement (source: Austin Raimond).

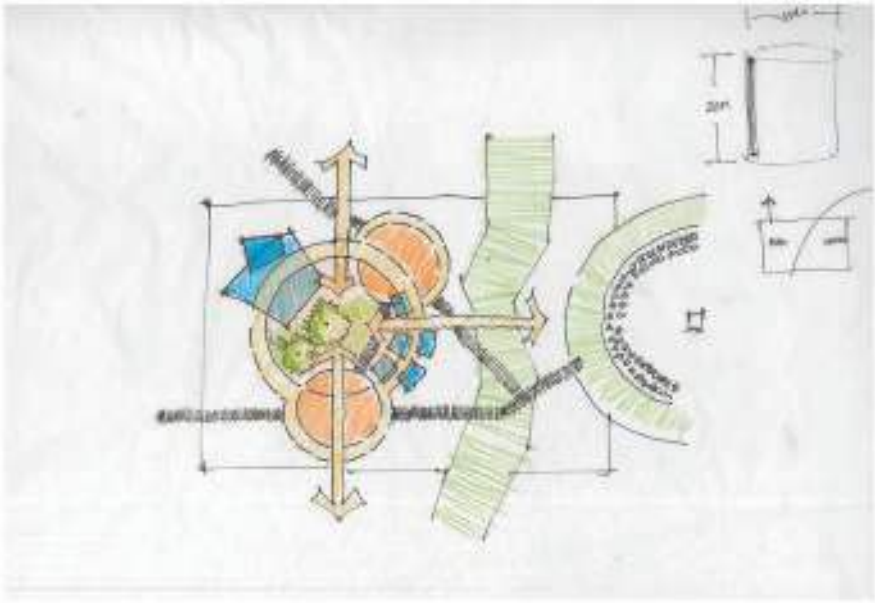

Figure 9.19: Early conceptual sketches of Raimond's proposed settlement (source: Austin Raimond).

Raimond integrates farming into these living spaces, establishing dedicated growing areas in the central courtyard and a spiraling, rising ramp around that courtyard (see Figure 9.19). The overall plan for the community is presented in Figure 9.20 (with a section presented in Figure 9.21), where a series of half-sunk domes accommodate much of the public spaces of the settlement, with additional housing deep below (protected from radiation). The envisioned public spaces include a fishery, gardens, and plaza, and other parks, with the separated workspaces in that southern wing and northwest extension accommodating additional housing. Figure 9.20 cleverly shows how various denizens of Raimond's settlement might live and work and where they might spend their time, putting a useful human touch to the plan.

With attention to human experience, integrating agriculture into living spaces, and an elaborate scheme of extensions and wings off of centralized domed structures, Raimond offers a scalable and modular design for a Martian city. His vivid illustrations do much to advance Sherwood's (2009) vision of a new profession of space architect and planner (introduced in Chapter 1), someone well versed in the science and engineering, as well as design and planning.

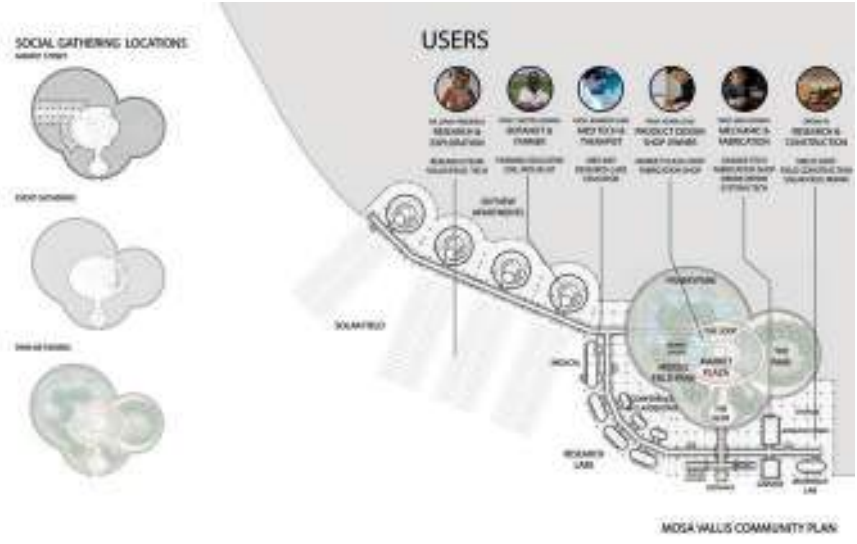

Figure 9.20: Community plan for Raimond's proposed settlement (source: Austin Raimond).

Figure 9.21: Section of Raimond's proposed settlement (source: Austin Raimond).

Mars World

Outer space architect, writer, and entrepreneur John Spencer has devised an elaborate plan for a city on Mars that can accommodate thousands of people.[4] I had the opportunity to speak with John at length about his work and plans for Mars. He generously shared with me an unpublished book he wrote, called *The Real Mars City Design* (December 2017). Ordinarily an unpublished book would not be an appropriate source for a precedent, but John Spencer is no ordinary writer, and his plan for Mars City is no ordinary plan (Figures 9.22 and 9.23).

Trained as an architect, Spencer has worked for NASA and numerous space industry contractors to design structures for outer space and interplanetary travel. Unlike many of the other fiction writers or aspiring designers I write about in this chapter, Spencer is actually a bona fide outer space architect. He has designed space architecture for scores of movies and television shows, carving somewhat of a niche in the entertainment world.

This is why "Mars World" should not be too surprising of a turn for Spencer. With a number of business, engineering, and finance partners, he is leading an effort to build a $2 billion amusement park (or what Spencer calls an "experience park") in either Las Vegas or China (Howell 2016). The plan is to attract 7 million people per year to a location that would simulate the experience of travelling to Mars and touring a Martian city there (Howell 2016).

[4] John Spencer is author of the book *Space Tourism—Do You Want To Go?* (Apogee Books Space Series, 2004) and wrote the foreword for this book.

Figure 9.22: Exterior rendering of Mars World (source: John Spencer).

Figure 9.23: Interior rendering of Mars World (source: John Spencer).

Like any good entertainment destination, the backstory and city plan for Mars City have to be well thought out and grounded in solid science and engineering. Spencer doesn't just want to build an amusement park: he sees Mars City as a prototype for a real city on Mars. His unpublished book *The Real Mars City Design* laid out the argument for the city's design and layout. He generously shared the book with me under the condition that I would only provide limited excerpts here.

Roughly, here is what his plan for Mars City entails: it begins on an impact crater located in close proximity to Olympus Mons – the largest mountain in the Solar System and an obvious tourist attraction. The basic design involves hollowing out from the rim of the crater in a tunnel along the rim's circumference, creating living spaces and an internal circulation system. There are two parts: above and below. In the below (underground zones), people live in residential quarters, and this is where infrastructure services, like water and waste storage and management, air production, farming, and some light manufacturing and maintenance uses, are housed.

The aboveground areas are where all the "entertainment, business, shopping and tourism areas" are housed (Spencer 2017, Section 3, p. 8). It is inside these rim areas that a promenade encircles the crater (2,100 feet long, 75 feet wide), like the "inside a large Earth based shopping mall" (Section 3, p. 8). Beyond the expected commercial and institutional uses, Spencer envisions a wide array of possible activities, each separated into 24 equally sized zones. The entire crater is not covered by a dome, as given the size, such a dome would be practically and economically infeasible. Instead, each zone is self-sufficient and maintains its own life support systems, such that a tragedy in one would not necessarily impact others, and people could simply move to a safe zone.

Spencer's plan envisions the use of smaller domes for events or special entertainment, or possibly for vertical farms 100 feet/30 meters in diameter. He notes that larger domes up to 300 feet/91 meters in diameter, as long as they are covered with protective soil, could be a feature of Martian colonization but are not part of the current plan (Section 3, p. 16).

Circulation roads surround the crater, presumably offering rover access. Aircraft are employed for transportation from the city through launch pads just outside of the rim. The rest of the city appears to rely on pedestrian internal circulation.

The Mars City plan considers nuclear power and the possible future use of fusion power, in addition to harnessing human energy through people spinning bikes. Food is to be grown hydroponically, and "major foods in the City will be fish, kelp and snails. These foods can be grown in large tanks of water that also function as radiation shields" (Section 4, p. 5).

Spencer's Mars City works as both a template for entertainment here on Earth and a template for the design of a real city on Mars. When and if Mars City is built on this planet, analysis of its design can allow for experimentation, renovation, and redesign, eventually informing the design of a Mars-based equivalent.

Conclusion

The precedents reviewed in this chapter offer some lessons and some warnings about approaching a design for a city on Mars. Each precedent advocates care in approaching site selection, with Spencer, Zubrin, the Mars Foundation, and Robinson each recommending a specific site, and Kozicka recommending a set of criteria that ought to be weighed. The variety in these precedents makes comparison somewhat difficult. Some describe urban plans for the immediate settlement and the following several decades (Zubrin and Kozicka), while others like Bradbury and Robinson have a longer view. This book is focused on a sweet spot between the two: not those first few years of early exploration, but rather the first several decades or more of permanent settlement, but before the fantastic science fiction vision of Robinson's Nicosia.

The architecture of moles, where natural light is absent, is not the aim. Chapter 11 presents a city plan that benefits from the protections afforded by natural landforms, but does not acquiesce to underground living. This plan builds on these precedents and the ones forthcoming in Chapter 10, along with the science and engineering best practices reviewed throughout this book, to present a compelling image of what a Martian city could be.

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10

Off-World Planning Precedents

The creative ideas presented in the previous chapter offer important lessons to inform the planning process for the first city on Mars. Other plans for humans to live off of Earth are equally valuable. In this chapter, I offer some particularly compelling examples, but do not promise anything nearing comprehensiveness. Such a task would require an entire book in and of itself.[1] Instead, this chapter is a concise overview of a select few plans. It begins with three buckets: serious plans developed by credentialed planning and engineering professionals and published in well-regarded outlets; perhaps slightly less serious plans published in less well-regarded outlets; and lastly, plans depicted in popular media like novels and movies. Like the previous chapter, I present key details for each plan and offer analyses of the major infrastructure, housing, architecture, and other dimensions, and conclude with a summary assessment of how the examples might shed light on a plan for a Martian city. In Chapter 3, I provided an overview of space exploration over the last seven decades and reviewed some plans for off-world living, including the ISS and the Artemis Plan for the Moon. Any plans reviewed in Chapter 2 will not be reiterated here.

[1] The closest thing might be Carl Abbott's (2016) *Imagining Urban Futures*, which reviews scores of science fiction books, films, and television shows in an attempt to understand how they depict cities and what that means for contemporary urbanism.

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J. B. Hollander, *The First City on Mars: An Urban Planner's Guide to Settling the Red Planet*, Springer Praxis Books, https://doi.org/10.1007/978-3-031-07528-5_10

Dalton and Hohmann's Lunar Colony Plan

In 1972, under contract with NASA, Dalton and Hohmann devised a detailed plan for a Lunar colony. The plan was grounded in broader concerns about urban planning at that time, as the authors explain:

> [an] observation or caution – this one fostered by a number of examples of American urban growth – is that many past colonies and cities have been programmed or designed for a specific size. When this size was established, no subsequent long-term planning was carried out. Growth thus became a random process which was not controlled by an ordered, rational management. In such circumstances, growth of the colony occurred without providing adequate support for the inhabitants, and services and infrastructural facilities (transport, environmental control systems, power, sewage, and even housing forms) were not distributed or integrated properly. (p. 375)

Instead of building an initial lunar base for a few dozen persons, Dalton and Hohmann argue for a thoughtful forecasting of how and where the base could expand into a larger settlement, and eventually into a city, and then integrate that thinking into the initial base design. They have done so in their plan for the Moon, as depicted in a scalable systems configuration for the base (see Figure 10.1) and a scalable plan for the layout of buildings and infrastructure (see Figure 10.2).

For the siting, the average temperature, temperature variation, sunlight, shade, mineral availability, astronomical considerations (where telescopes, particularly radio ones, will be most effective), earthlight, and eclipses (they occur twice per year and cause extreme drops in temperature on the lunar surface) were all considered. The decision was to site the colony in the Kopff Crater at roughly 17.5 degrees S latitude and 89.5 degrees W longitude, away from the lunar poles. Energy for the colony would come from nuclear and solar power sources, while transportation around and beyond the colony would be conducted by surface vehicles, some version of a lunar rover (Figure 10.3).

There are nine canister units for initial landing crew (see map location 1 in Figure 10.2), which are then expanded by additional sets of canister units (map locations 2, 5, 7) and farm modules (3, 4, 6, 8). Later, the plan envisions construction for local materials, large work buildings (9, 10), a large farm structure (11), and a food storage structure (12). Lastly, the plan calls for the building of significantly larger structures (13,14,15) that would give colonists what Dalton and Hohmann (1972) call "a luxurious quantity of space" (p. 81).

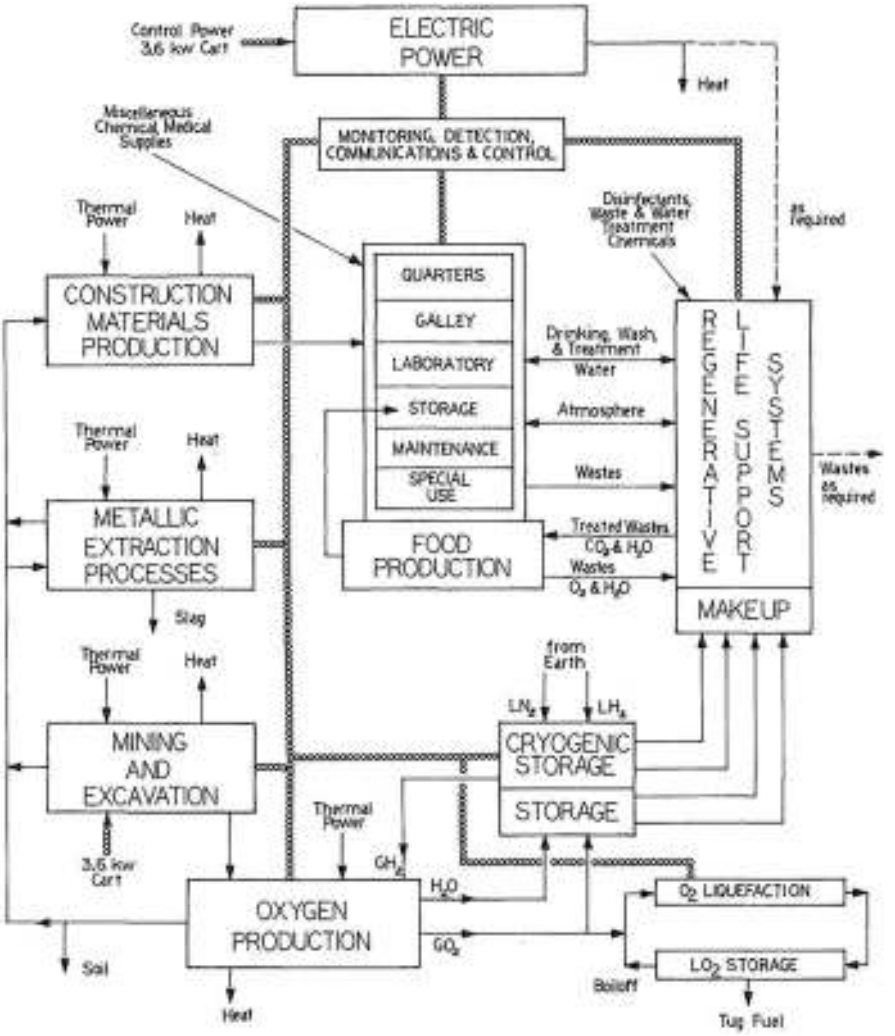

Figure 10.1: Systems plan for a lunar colony (source: Dalton and Hohmann 1972).

The lunar planners considered other configurations, but selected this initial framework because they felt that lunar colonists on location would be best positioned to respond to their unique environments to fine-tune the specifics of the layout and configuration of the settlement: "the additional effort and ingenuity that a team of colonists are likely to put forth for construction of 'their' colony will undoubtedly be an asset in the lunar environment" (p. 83).

The Dalton and Hohmann plan is one of the first and most thorough plans for human settlement on the Moon. Ever since its publication in 1972, it has

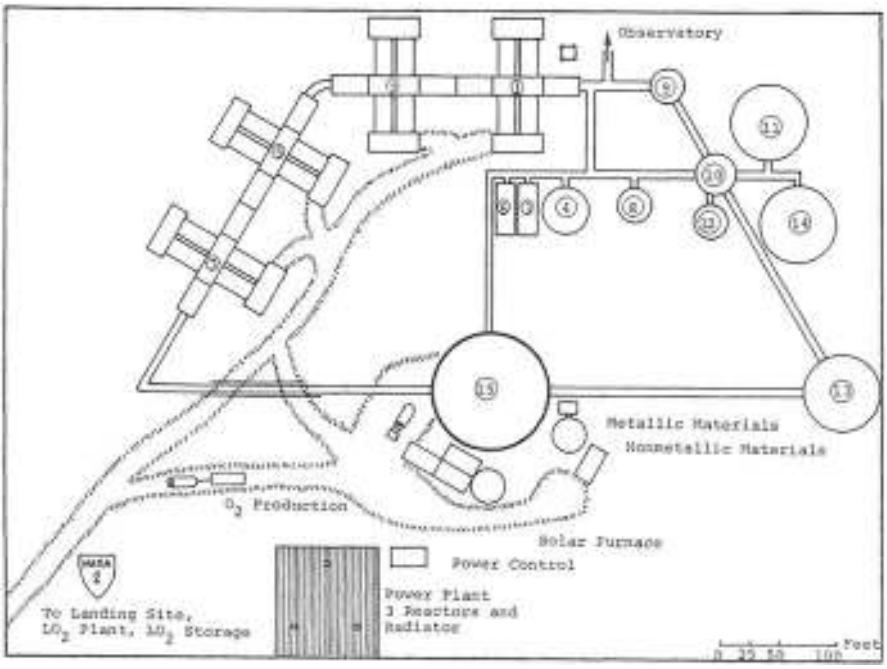

Figure 10.2: Conceptual plan for a lunar colony (source: Dalton and Hohmann 1972).

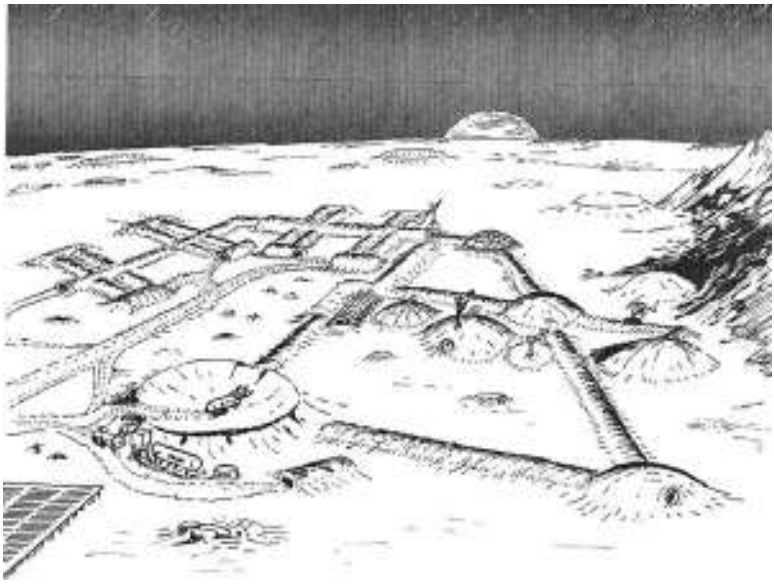

Figure 10.3: Surface view of a proposed lunar colony (source: Dalton and Hohmann 1972).

been cited scores of times by scientists and engineers grappling with similar questions. New discoveries in planetary sciences as well as on-Earth advances have eroded some of Dalton and Hohmann's ideas. But their basic view of the need for long-range thinking even in designing a first-landing base on the Moon is very important to the work of this book. The modular and scalable features of their plan, and their insistence that colonists will need to play a crucial role in refining it, also has great salience today and is relevant in the plan presented in Chapter 11.

Turning Dust to Gold on the Moon

Rutgers University Engineering Professor Haym Benaroya authored *Turning Dust to Gold: Building a Future on the Moon and Mars* in 2010. The book's plans for Mars are instructive and informed a lot of the earlier chapters of this book. I chose not to profile those plans in Chapter 8 because doing so would have been repetitive of other precedents in that chapter. However, Benaroya's plans for colonizing the Moon are more distinctive and deserve close examination here.

Benaroya begins by siting his Moon settlement underground in lava tubes, like those described in Chapter 9 in the Prairie View team's proposal for Lavapolis on Mars (Benaroya 2010, p. 195). Like on Mars, these cavernous tunnels are believed to have been formed as lava flowed through and left behind stable basalt tubes as wide as 300 meters, 40 meters below the lunar surface (Coombs and Hawke 1992; York, et al. 1992).

For housing the denizens of this lunar colony, Benaroya begins by estimating the living and working area needs of each resident and concludes that 120 cubed meters is sufficient. This is roughly the amount that astronauts on the ISS are each allotted. Regarding the layout of habitats, Benaroya considers three possibilities: radial (linear segments extend from a major central space, like the Prairie View Hexamars design presented in Chapter 9), branching (small circulation pathways extend from main ones), and cluster (a layout without any legible circulation pattern). Benaroya proceeds with the radial layout plan, conducting extensive engineering analysis to establish its primacy over the other two layouts (see Figure 10.4). Regarding infrastructure, Benaroya proposes the use of solar and geothermal energy to be harnessed in situ.

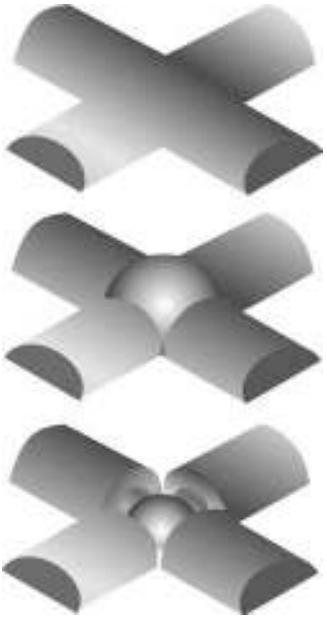

Figure 10.4: Three structural concepts (source: Aliya Magnuson, adapted from Benaroya 2010).

Selenia: Third Generation Lunar Base

A team of students and faculty from the University of Puerto Rico sketched a possible lunar settlement, imagining what they called a "third generation" base where 100 lunar denizens can permanently live and work, largely self-sufficiently. Like the Prairie View project presented in Chapter 9, this work was supported by funding from NASA. The basic layout of the settlement involves the following:

> 120-ft-diameter craterlet covered by a geodesic structure with tunnels to house underground personal quarters… Three Social Nodes will be located at the juncture of the tunnels, each containing a lobby-lounge, a gym, a galley, a dining-conference-library area, an infirmary, a chapel, and a surface-access igloo. (University of Puerto Rico 1991, p. 266).

The four-level craterlet serves as the heart of the settlement, where life support systems recycle wastes and generate fresh water and air, and where food is grown and stored. An elaborate underground tunnel system connects the nodes to one another, and rovers are used to explore the lunar surface (Figure 10.5).

Notable about the Selenia plan is its embracement of partial underground living, dome features, and the central large spaces connected with spokes to a network of other nodes – all familiar patterns seen earlier in this chapter and in the previous chapter.

Space Settlements

There are places to orbit a space settlement around the Earth, Moon, or both that provide the optimal proximity to the Earth and Moon, without being too close to suffer from too frequent eclipses. These libration or Lagrange points are numbered one through five. The 1975 NASA Summer Study decided that

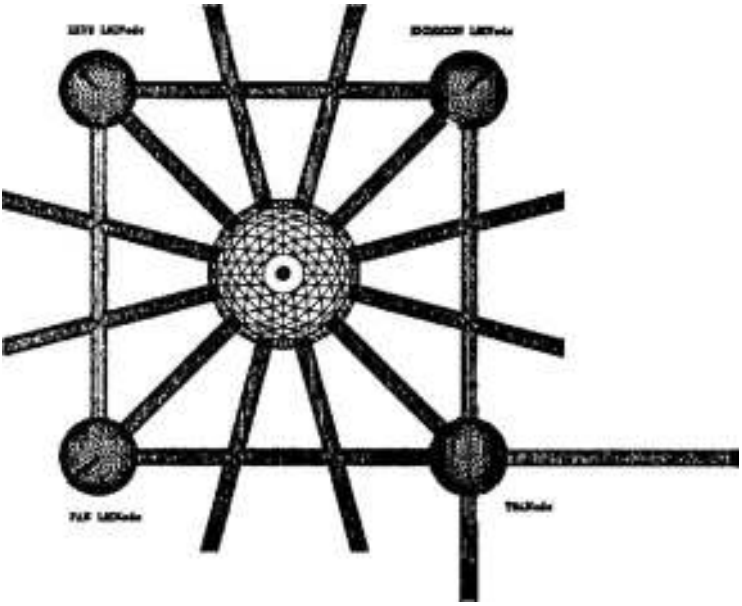

Figure 10.5: Plan view of the Selena lunar settlement (source: NASA, University of Puerto Rico 1991).

they would design an orbiting settlement at libration 5, aka L5 (see more details on Lagrange points and a conceptual map of the "human accessible" Solar System in Chapter 3).

Convening some of the top scientists and engineers at the time, NASA sought to explore a range of possible configurations for settling space, the efforts of which resulted in an important publication and an impressive set of color illustrations (NASA 1975). The famous Bernal Sphere, O'Neill Cylinder, and Stanford Torus each represented a different approach to off-Earth settlement, and the NASA Summer Study involved a detailed examination of each (Figure 10.6).

John Desmond Bernal first proposed the spacecraft sphere concept in the 1920s, which later came to bear his name. The Bernal Sphere was a major feature of the 1975 NASA Summer Study (Alshamsi, Balleste, and Hanlon 2018). The design was intended to accommodate 75,000 people (see Figures 10.10, 10.11, and 10.12). That sphere was then expanded upon in Princeton University Professor Gerard O'Neill's book *The High Frontier* (1977), where he identified three habitat variations he called Islands 1,2, and 3. The Bernal Sphere was Island 1. A cylindrical settlement was identified as Island 2 (which came to be known as the O'Neill Cylinder), and a ring or Toroidal shape was Island 3. In *The High Frontier*, the Bernal Sphere was presented as 500 meters in diameter but could be built as large as 19 kilometers

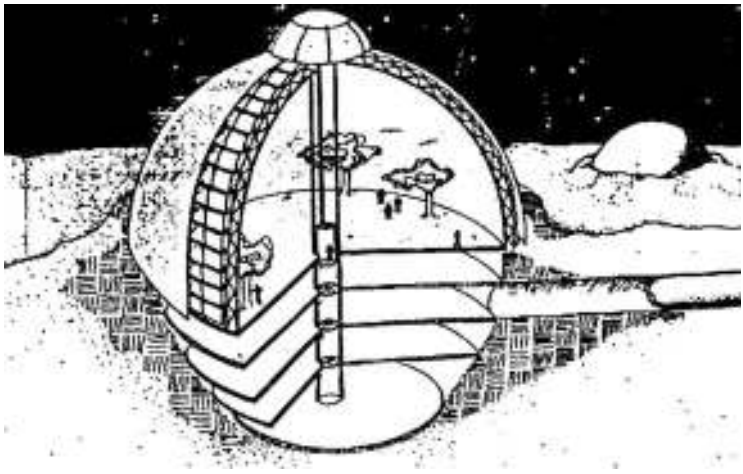

Figure 10.6: Rendering of the Selena lunar settlement (source: NASA, University of Puerto Rico 1991).

in diameter. It was replete with "low-rise, terraced apartments, shopping walkways, and small parks" (p. 11). Services and industry were placed underground so as to reserve most land for "grass and park" (p. 11). The sphere was occupied by 10,000 residents and featured many Earth-reminiscent amenities like movie theatres and performance spaces for ballet and concerts. The popular television science-fiction show, Babylon 5 (1993–1998), was set on a Bernal Sphere (Scharmen 2019).

The second Island introduced in *The High Frontier*, the O'Neill Cylinder (named after the author), was designed to house 820,000 people and was sited at EM L4 or L5. In the NASA Summer Study, concepts for O'Neill Cylinders were two miles in radius and 12 miles long, accommodating ten million people (Scharmen 2019, p. 100) (see Figure 10.7).

According to Scharmen (2019), the illustrator of the O'Neill Cylinder design, Stewart Brand, was directed to depict landscapes akin to a French countryside (see Figures 10.8 and 10.9). The illustrator succeeded in conveying such an idea, with rolling hills, magnificent vistas, and well-placed greenery. The NASA team sought to create six equal sections in the cylinder, three valleys, medium-sized cities at both ends, and small villages and forests in between. Agricultural and industry were located outside the main cylinder (Scharmen 2019, p. 101). A fully manicured and controlled environment, the

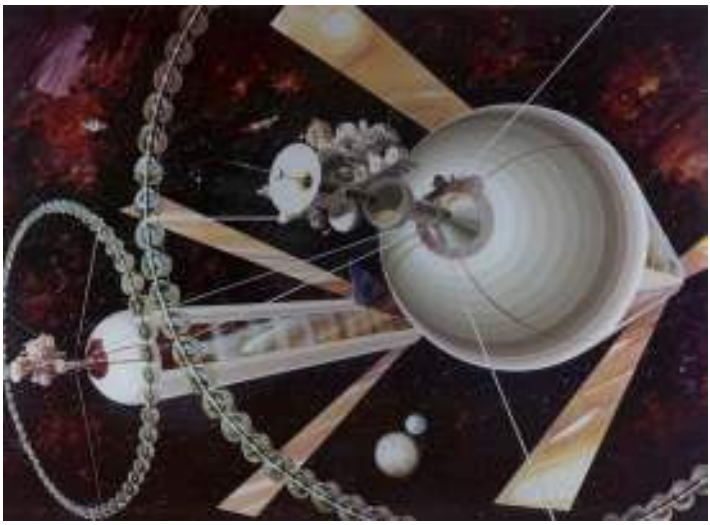

Figure 10.7: Exterior view of a double cylinder colony using the O'Neill Cylinder design (source: NASA Ames Research Center).

Figure 10.8: Interior view with a long suspension bridge using the O'Neill Cylinder design (source: NASA Ames Research Center).

Figure 10.9: Interior view down the length of the cylinder, looking through large windows at the Earth and Moon (source: NASA Ames Research Center).

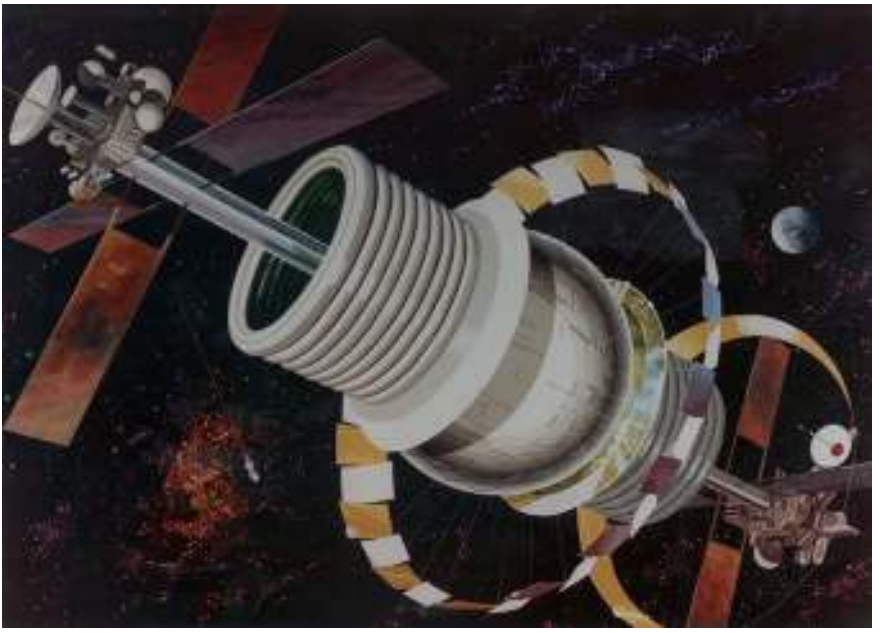

Figure 10.10: Exterior view of the Bernal Sphere design (source: NASA Ames Research Center).

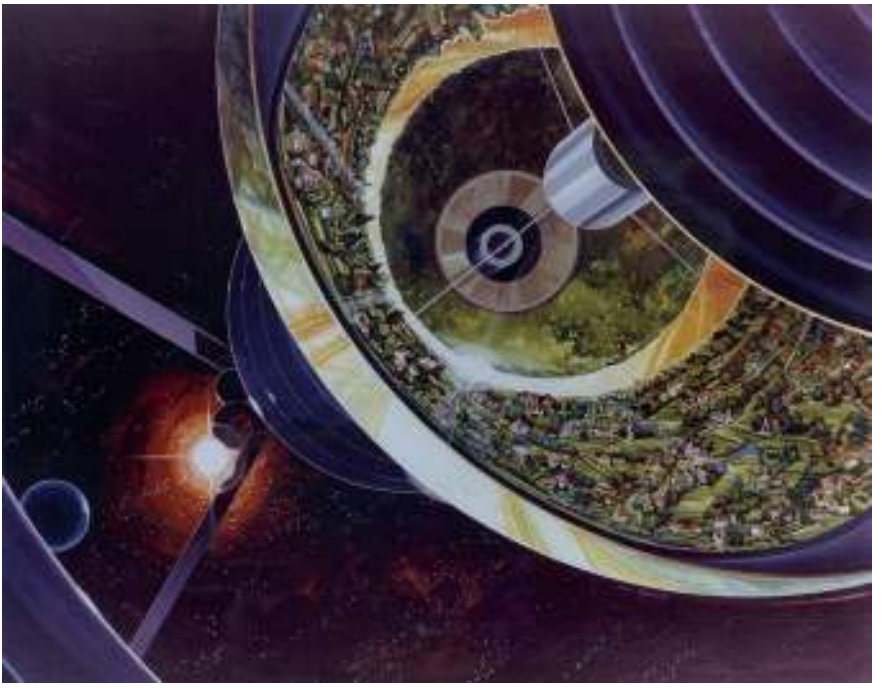

Figure 10.11: View with cutaway to see the interior of the Bernal Sphere design (source: NASA Ames Research Center).

Figure 10.12: Interior view of the Bernal Sphere design (source: NASA Ames Research Center).

O'Neill Cylinder was a place with no pests. Scharman (2019) writes, "Part Eden, part Ark, O'Neill's constructed landscape exists as pure amenity. In a kind of super-Corbusianism, not just the city by this whole world is a park built on artificial raised ground" (p. 106). Notably, an O'Neill Cylinder was featured in Christopher Nolan's film *Interstellar* (2013) as Cooper Station, which accomplished that same countryside feel.

Employing a toroidal shape, the Stanford Torus designs from the 1975 Summer Study were built to accommodate 10,000 people each (Scharmen 2019, p. 49). The toroid itself is the same shape of a tire, and in fact, the Goodyear Tire Company was heavily involved as early as 1957 in conceptual designs (and even a scaled replica) of space stations (see Figure 10.13) (Nesbit 2020, p. 40).

For the 1975 NASA Summer Study, the Stanford Torus involved raised platforms and layers designed to separate living areas with transportation, utilities, and other infrastructure (Scharmen 2019, p. 117) (see Figures 10.14, 10.15 and 10.16). Hillside terraces where "one many'd deck... was another guy's roof" (p. 117, as quoted from Guidice, Rick. 2015 interview with Scharmen). Additionally, the space was highly segregated, with "services below a public ground and higher-speed transportation above. The terraced housing

Figure 10.13: The toroidal-shaped space station model by the Goodyear Aircraft Company, which closely resembles a giant tire (source: NASA Langley Research Center).

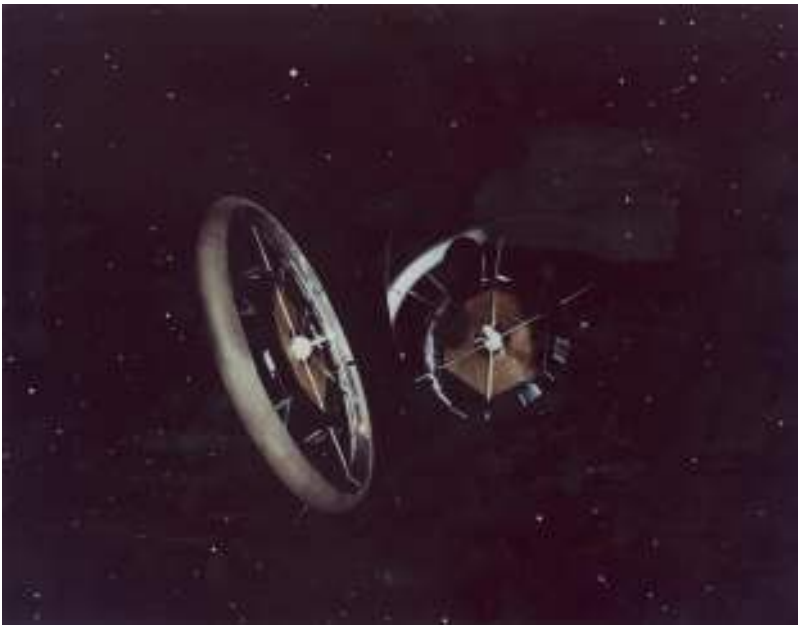

Figure 10.14: Exterior view of the Stanford Torus design (source: NASA Ames Research Center).

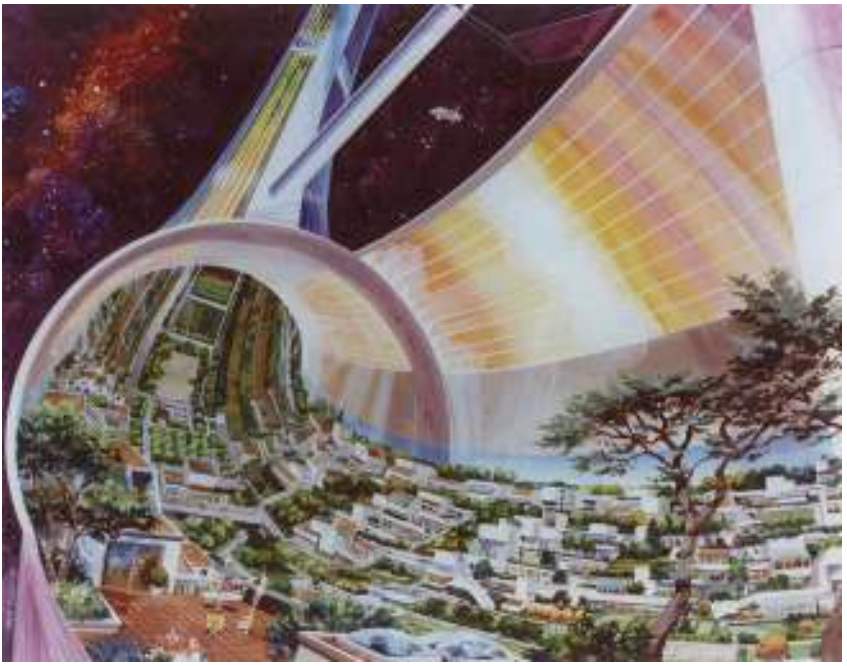

Figure 10.15: Cutaway view exposing the interior of the Stanford Torus design (source: NASA Ames Research Center).

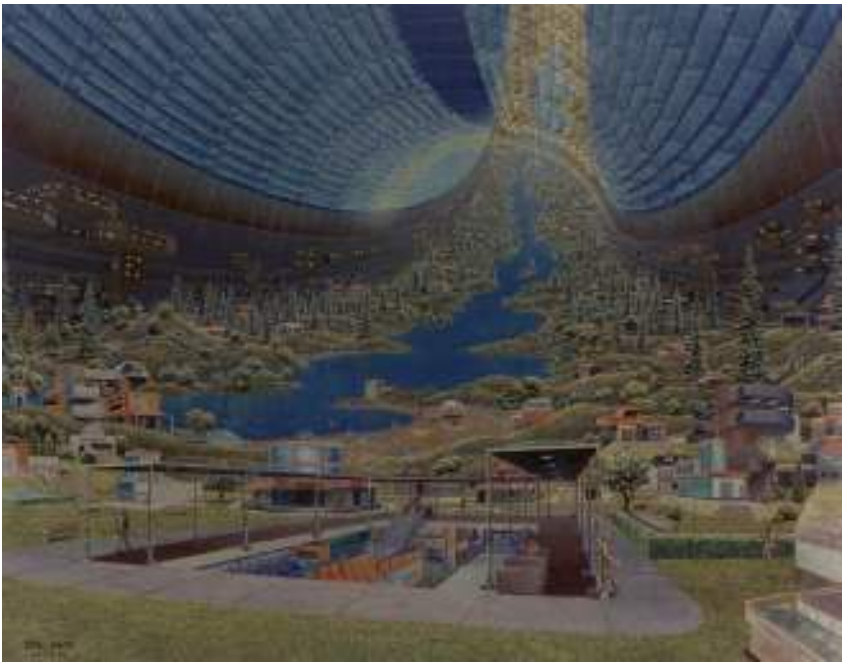

Figure 10.16: Interior view of the Stanford Torus design (source: NASA Ames Research Center).

multiplies the ground plane above all of that, with private gardens, light and air, for everyone" (Scharmen 2019, p. 119). The lowest levels of the space station, "with no direct access to light and air," were for "storage, processing, and waste treatment" (p. 125).

The Stanford Torus has been fairly impactful in popular culture, the blueprint for the orbiting space station featured in Neill Blomkamp's 2013 film *Elysium*. The exterior double toroidal shape in the movie houses a wealthy enclave of elites, "an exclusive, luxurious and securitized gated community in space for the propertied rich" (Mirrlees and Pedersen 2016, p. 309). Instead of depicting the landscape akin to a French countryside, the filmmakers instead chose a well-manicured, heavily lawned North American suburban community feeling with oversized mansions and lavish pools. The film's social critique sets up the Elysium station as a welcome alternative to life on Earth, ravaged by pollution, disease, and exacerbated inequality, using the Stanford Torus design to showcase a desirable, amenity-filled place to live (Mirrlees and Pederson 2016).

These three space settlement designs – Bernal Sphere, O'Neill Cylinder, and Stanford Torus –offer important insights into off-Earth living and inspiration for a Martian city.

SOM's Moon Village

At the time of this writing, the leading architecture and planning firm Skidmore, Owings & Merrill (SOM) is heading an effort to design a Moon Village in collaboration with the European Space Agency and the Massachusetts Institute of Technology (MIT). Georgi Petrov was the primary author on a paper outlining the team's plan, published as part of the proceedings of the 49th International Conference on Environmental Systems in Boston, 2019. Not wanting to seem impractical or unbounded to reality, the Moon Village planners write that "The project would allow us to build on knowledge and technologies for space applications that will in turn advance our approach to more intelligent methodologies for terrestrial utilization and promise to directly impact how we approach challenges back on Earth." (p. 2).

This was not the first time Petrov had explored space architecture and planning. For his 2004 Master's thesis in Architecture at MIT, he first began to sketch out the ideas later expressed in the Moon Village concept. In those early sketches, Petrov developed a plan for a city on Mars. The concerns and limitations of building on Mars translated quite well to the lunar surface, where the Moon Village concept came to life.

Petrov et al. (2019) began by siting their permanent settlement on the lunar south pole, arguing that water, methane, ammonia, carbon dioxide, and carbon monoxide have all been detected there, making in-situ resource utilization possible. On the rim of Shackleton Crater, the SOM team is "maximizing exposure to near continuous daylight and maintaining an unobstructed line of sight of the Earth" (p. 5).

The team introduced their master plan by stating their engineering requirements of safety, efficiency, and expandability. Next, they grounded their plan in historic terrestrial development, citing Arturo Soria's 19th century plan for Ciudad Lineal, the district in Madrid, and Le Corbusier's Linear City concepts – just as the Mars Foundation did in its Homestead plan introduced in Chapter 9. The linear city moves along a path, roadway, or rail line, each module connecting sequentially with the next. For Moon Village, the SOM Team created four parallel bands "that are connected at regular intervals [and] best achieves the goals of safety, efficiency and expendability" (Petrov et al. 2019, p. 5) (See Figure 10.17). The first band is designated for residential use and sits closest to the crater. The second band is designated for infrastructure, while the third band is for various activities like offices, staging areas, or other work spaces. A fourth band is dedicated to energy generation and transportation activities (see Figure 10.18). The plan also features what the team calls a "Pristine Lunar Park," where development activities are prohibited in order to maintain a zone with unobstructed views of Earth (see Figure 10.19).

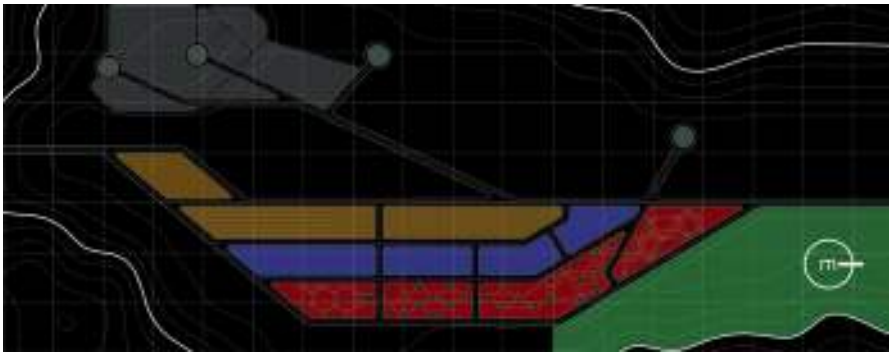

Figure 10.17: Master plan for Moon Village. The green zone is the Pristine Lunar Park, red are residential areas, blue includes infrastructure, and orange hosts other activities for commerce or scientific exploration. Notably, instead of the commonplace north arrow seen on terrestrial maps, the arrow icon on the lower right corner of the plan indicates the direction towards Earth (source: Skidmore, Owings & Merrill served as the architect, structural engineer, and designer of the master plan. Image credit: Image (c) SOM).

Arrayed inside the residential band closest to the rim of the crater is a series of vertical habitats linked to one another (see Figure 10.20). Each vertical habitat is multi-storied and features central atriums surrounded by three nodal zones. The nodal zones host a range of use categories, from residential

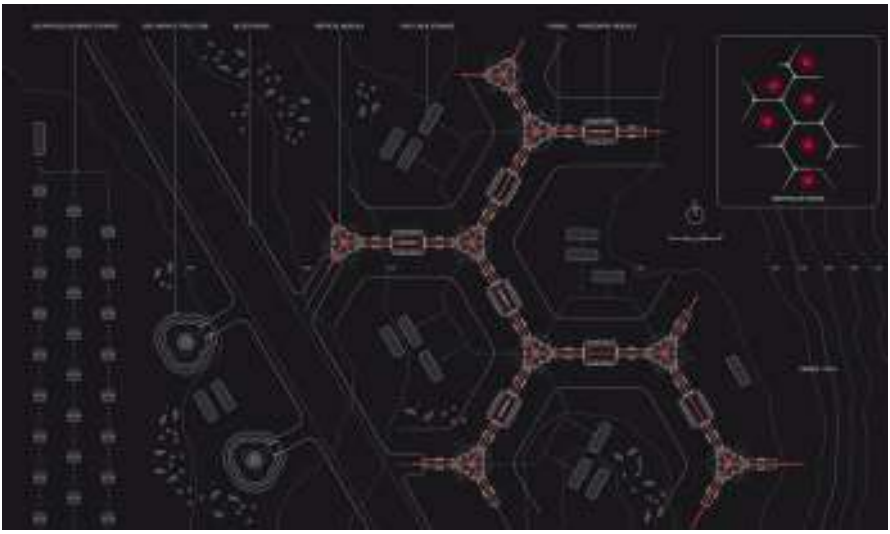

Figure 10.18: Plan view rendering of Moon Village (source: Skidmore, Owings & Merrill served as the architect, structural engineer, and designer of the master plan. Image credit: Image (c) SOM).

Figure 10.19: Eye-level rendering of Moon Village with a view of Earth (source: Skidmore, Owings & Merrill served as the architect, structural engineer, and designer of the master plan. Image credit: Image (c) SOM | Slashcube GmbH).

(crew quarters), to laboratories, to exercise and food preparation areas (see Figure 10.21).

The SOM Team created a visually compelling and well-organized plan for a permanent lunar settlement, grounded in state-of-the-art science and engineering and coauthored with some of the leading astronautical minds in the world. While permanent, Moon Village is quite small, and scalability is not well articulated due to the lack of any meaningful transportation system. The addition of new linear elements makes it possible for the Moon Village to grow quite large (as the Saudis imagine in their linear city on Earth; see Chapter 9), but circulating people, equipment, and cargo may present challenges over time.

Beyond that limitation, the Moon Village concept is quite informative for Martian city planning. The residential habitats present a clear and efficient means to house a variety of human functions, provide public gathering spaces, maintain open spaces in central atriums, and preserve long vistas of the lunar landscape and beyond to planet Earth.

Summary

These precedents offered the perspective of city building from the Moon and beyond, complementing the precedents introduced in the previous chapter that focused solely on Mars. Thoughtful arrangements of structures and transportation routes across a range of axes, both surface-level and belowground,

Figure 10.20: Aerial-view rendering of Moon Village (source: Skidmore, Owings & Merrill served as the architect, structural engineer, and designer of the master plan. Image credit: Image (c) SOM | Slashcube GmbH).

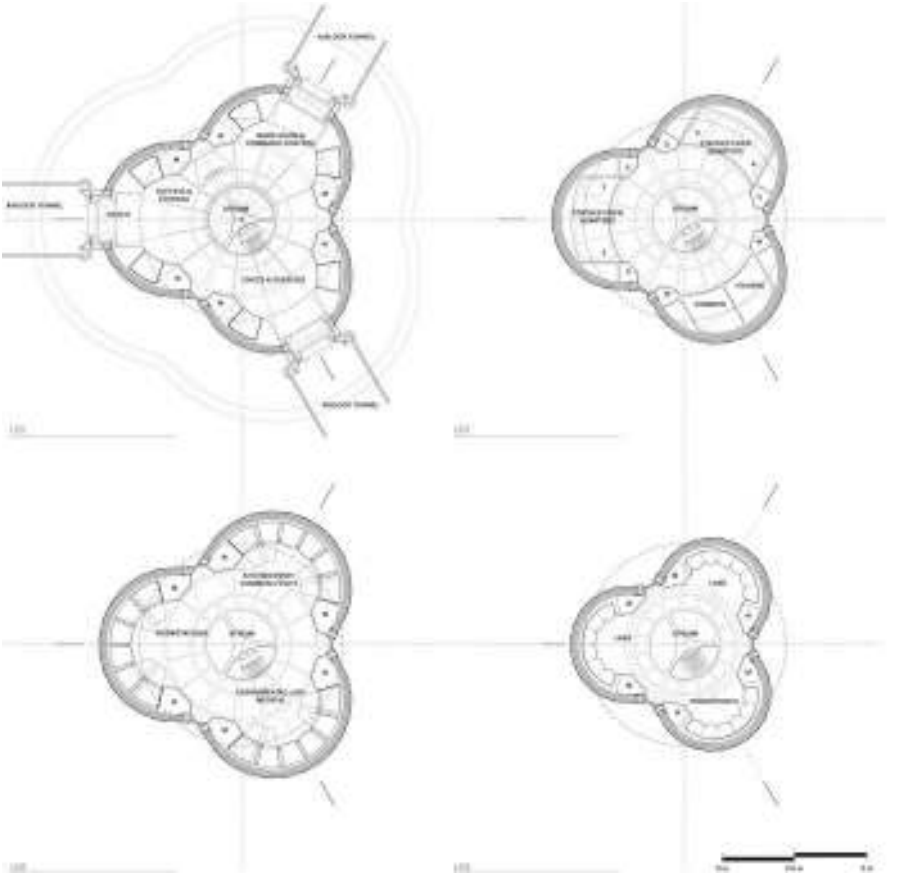

Figure 10.21: Interior diagrams of vertical habitats in Moon Village (source: Skidmore, Owings & Merrill served as the architect, structural engineer, and designer of the master plan. Image credit: Image (c) SOM).

building on human needs to be connected to greenery and "nature," and providing important vistas, should all be considered when planning a city on Mars. These precedents need to be understood in the context in which they were created, the funding that supported them, the composition of each team, and the state of knowledge at the time they were conceived. With those limitations in mind, the following chapter attempts to draw from the best of each to present a clear vision of a city on Mars. In the process, it seeks to generate something novel, contributing to the broader space architecture and urbanism conversation and offering a template for future explorers.

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11

A Template for a Mars Colony

My greatest contribution in the preceding pages has been my serious examination of several key principles for Mars city building and my effort to make sense of the results. I would be content (on some level) with ending the book here. However, I have learned from the great urban planners of the past[1] that a set of principles is not enough to capture people's imagination – people want to see a plan, they want to see renderings, and they want to imagine what life in such a place would really be like. In that spirit, I endeavored to develop the following plan for the City of Aleph on Mars.

City planning involves trade-offs, winners and losers, and compromise. As such, the following plan does not address all principles equally or fairly. It is my attempt to build a vision for a Martian city and it is imperfect. I hope that these plans will be used by others as they advance their schemes to settle Mars, but the *principles* are what I really care about. Other plans can certainly be developed from these principles.

The earliest written plans for cities in Mesopotamia, three thousand years before the Common Era, laid out paths for streets and the locations of major structures (Frankfort 1950). These proto-urban plans were, arguably, monumental markers in the progress of human civilization. As the previous chapters demonstrate, city planning here on Earth has encountered many (though certainly not all) of the same challenges that we might expect to face on Mars and provides the context for devising a plan for Aleph City, the first city on Mars.

[1] Daniel Burnham, widely regarded as the father of modern urban planning, wrote: "Make no little plans; they have no magic to stir men's blood and probably themselves will not be realized. Make big plans; aim high in hope and work, remembering that a noble, logical diagram once recorded will never die, but long after we are gone be a living thing, asserting itself with ever-growing insistency" (Moore 1921, p. 147).

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J. B. Hollander, *The First City on Mars: An Urban Planner's Guide to Settling the Red Planet*, Springer Praxis Books, https://doi.org/10.1007/978-3-031-07528-5_11

Rocket scientists, geologists, chemists, food scientists, physicists, engineers, and hydrologists have been the main actors on various teams planning to travel to and colonize Mars. Yet most of those experts do not have a formal urban planning background.

The plan that follows rests on seven decades of space exploration (Chapter 2), a systematic review of the history of colonization efforts here on Earth (Chapter 3), the psychological and biological needs of people in their physical environments (Chapter 4), best practices in urban transportation (Chapter 5), residential, commercial, and industrial development (Chapter 6), building science and engineering (Chapter 7), infrastructure (Chapter 8), and the experiences of others who have devised plans for Martian cities (Chapter 9) and other off-Earth cities (Chapter 10). This foundation, formed with the help of numerous research assistants,[2] helps to strengthen the viability of this new city plan.

Guiding Principles

Throughout the previous chapters, my investigation across a number of topics led to a set of principles to guide the development of this plan. Below are the 30 principles, organized by chapter:

Colonization Lessons

1. New Town Site Selection: ideally, flat sites with access to drinking water, transportation, and proximate natural resources (e.g. mining and forests).
2. Street Design: climate considerations (e.g. wind) should drive the layout and configuration of streets; connectivity is paramount.
3. Public Spaces: centrally located public gathering spaces are essential; access to sunlight and greenery should be integrated.
4. Prominent Public Buildings: in or close to the central public gathering spaces should be reserved a location for important public buildings, including governmental and market uses.
5. Spirituality: the form, uses, and design of the settlement should consider metaphysical dimensions.

[2] Berk Diker played a critical role in providing research assistance through the book and served as my partner in the design of Aleph City, creating all of the maps and renderings herein.

Environmental Design and Psychology Considerations

1. Edges Matter.
2. Patterns Matter.
3. Shapes Carry Weight.
4. Storytelling is Key.
5. Biophilia Counts.

Transportation Dimensions

1. Adoption of a primary mass transit that uses multiple tracks and is underground.
2. Development of a secondary pedestrian and bike transport system underground.
3. Creation of a tertiary rover system that relies on rough surface roadways.

Residential, Commercial, and Industrial Dimensions

1. Design for high-density, mixed-use development.
2. Initial commercial functions can include mining, tourism, private research, and support functions. Over time, settlements could be developed enough to get involved in trade operations within their own borders and with other settlements.
3. In regions with extreme climates, access to amenities must be incorporated into the design from the beginning rather than being introduced at a later date.
4. Extreme climates demand compact and intensive textures, small and enclosed areas, narrow passages along the ground level, and layouts that take advantage of the position of the Sun.
5. The settlement must be hermetically sealed to protect the residents from the hostile atmosphere outside.
6. Radiation exposure on the surface must be taken into consideration when designing structural openings and exposed surfaces.

Building Science, Design, and Engineering Dimensions

1. Some construction materials may need to be brought from Earth, like metals, fabrics, and membranes, but minimally manufactured regolith can produce the remaining needed materials like bricks, ceramics, glass, and concrete.
2. Various modular building structures and forms will be needed for Aleph, but domes represent the ideal shape for reducing heat loss.
3. Construction accomplished remotely or by robot prior to human settlement will reduce potential human harm, thus, 3D printing methods ought to be utilized whenever possible.
4. Ample natural light and views from the interiors of buildings are a necessary consideration in building design.

Infrastructure Dimensions

1. Water can be collected from the Martian atmosphere, effectively stored, and reused so as to reduce evapotranspiration.
2. Infrastructure should be flexible and open to expansion over time, designed and built around reusing and recycling precious natural resources.
3. Supply and return infrastructure for industrial and commercial functions should be separated to avoid cross contamination.
4. Food can be grown primarily from plants and single-cell proteins (SCPs) in a mix of aboveground greenhouses and belowground hydroponic facilities.
5. Heat and electricity can be generated from nuclear, solar, and methanol through the use of redundant and autonomous cleaning and repair systems whenever possible.
6. Nuclear reactors can be employed to regulate the temperature of the city, where sunlight can be directed into the settlement as a supplemental heating source.
7. Recycling and reuse facilities are essential for managing waste to ensure that finite resources (materials, food, water, energy) are conserved.

Site Selection

A key consideration in finding a site for Aleph City is the location where ships will land from Earth. On Earth, ports have driven urbanization since ancient times, from the deep harbors of Lisbon, Portugal to LAX airport in Los Angeles, U.S. The location of a Martian port will be shaped by many factors, involving a roughly 25-square-mile flat zone with few craters or large boulders and with primarily hard surfaces (Gallegos and Newsom 2015). Wamelink's et al. (2014) research also suggests that soil quality varies significantly across Mars, and a landing site should most strongly consider those zones most suitable for plant growth (see Figure 11.1). Cohen (1996) emphasizes the need for a settlement site to be relatively flat and absent any particularly tall geological features within 1–2 kilometers (to ease flight access), proximate to natural resources in Martian regolith, and soil that can sustain 60–65 metric tons of equipment and spacecraft. Fergason et al. (2017) has also written about the need for a landing site to be flat, with slopes not exceeding 15 degrees. The European Space Agency (2021) has called for a landing site also to be flat and close to the equator. The Martian equator, like the equator on Earth, is the planet's closest region to the Sun and enjoys the most heat and sunlight – all useful for generating solar power and for maintaining warmth). NASA (2021) published a number of criteria:

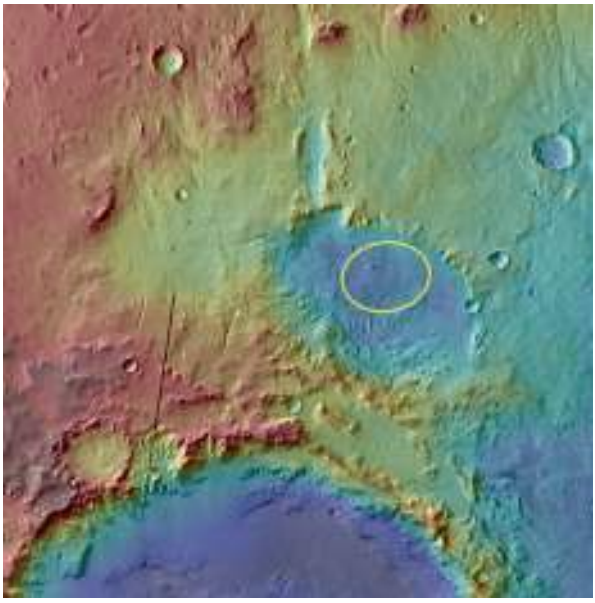

Figure 11.1: Eberswalde Crater, one of four finalist landing sites for NASA's Curiosity rover (source: NASA).

– Evidence of past or presently habitable environment
– Geological record that includes exposed rock layers
– Evidence of water (past or present)
– Smooth and safe area

NASA's Mars Science Laboratory, also known as the Curiosity rover, considered these criteria in narrowing down a list of 100 possible sites to four finalists for a Mars landing: Eberswalde Crater, Holden Crater, Mawrth Vallis, and Gale Crater (see Figures 11.1, 11.2, 11.3, and 11.4 and Table 11.1). The Curiosity mission focused on scientific exploration and not long-term human settlement, so its criteria would certainly be different than settlers'.

The NASA team eventually selected Gale Crater, and Curiosity landed there on August 12, 2012 (see Figures 11.5 and 11.6). At the time of writing, Curiosity is still traversing the crater and surrounding environment (NASA 2021). Gale Crater was a strong candidate for landing in part due to its exposed layers of rocks, some up to 5 km high, which allowed scientists to study the environmental change expressed in each layer (Wray 2013). Some have theorized that Gale Crater may have been a lake, and part of Curiosity's mission was to attempt to detect evidence of water in the region (Wray 2013). Curiosity did find what may have been an ancient streambed (Administrator

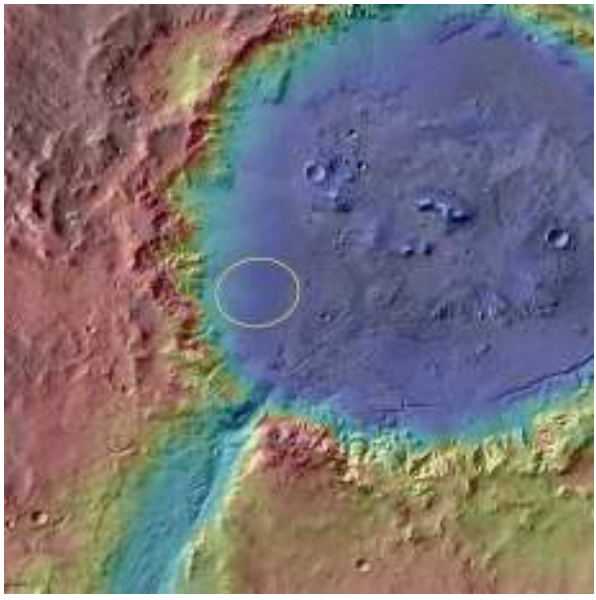

Figure 11.2: Holden Crater, one of four finalist landing sites for NASA's Curiosity rover (source: NASA).

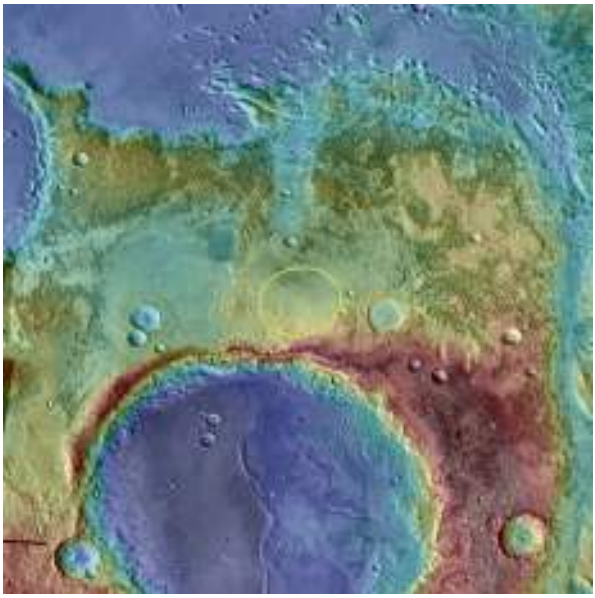

Figure 11.3: Mawrth Vallis, one of four finalist landing sites for NASA's Curiosity rover (source: NASA).

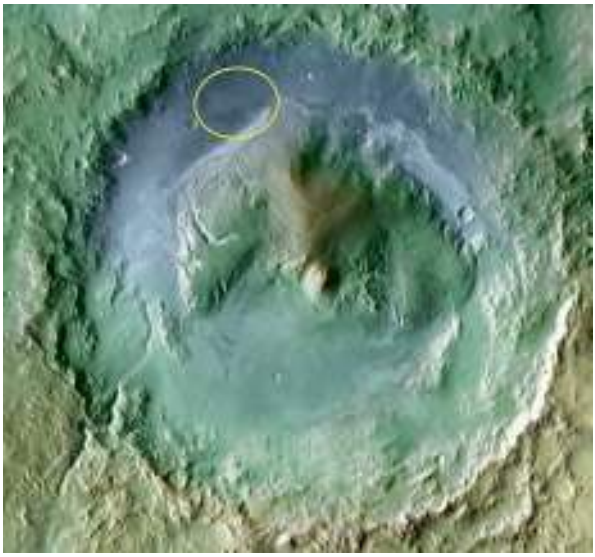

Figure 11.4: Gale Crater, one of four finalist landing sites for NASA's Curiosity rover (source: NASA).

Table 11.1 Suitability of Four Landing Sites

Potential Sites	Holden Crater	Eberswalde Crater	Mawrth Vallis	Gale Crater
Advantages: Scientific or Economic Objectives	The history of water on Mars can be explored in the area by examining erosion on deposits of over 3 billion year old sediments The area contains some of the most ancient rocks There are clays and megabreccia of geologic interest Deposits are exposed in a possible ancient lake There is a smooth, flat surface fit for a safe landing ellipse Thermal inertia/ surface material is consistent	The history of water on Mars can be explored in the area by examining a delta containing clays The area contains features such as the evolution of a crater lake and a sedimentary depositional that may have potentially preserved organic material	Early habitability on the planet can be explored in this area The area may be representative of global conditions on Mars Rocks contain more than 50 % phyllosilicate (sheet silicates) minerals - which have potential for biological preservation	Strata contain hydrous minerals and indicate a record of aqueous environments

(*continued*)

Table 11.1 (continued)

Potential Sites	Holden Crater	Eberswalde Crater	Mawrth Vallis	Gale Crater
Disadvantages: Scientific or Economic Disadvantages	The environmental history is unclear The environment may not be well suited to preserve potential biological sediments	There is a limited variety of phyllosilicate (sheet silicates) minerals - which have potential for biological preservation The science in the landing ellipse is secondary the science outside the ellipse	The depositional setting and process for concentrating or preserving organics are unclear	There is a limited variety of phyllosilicate (sheet silicates) minerals - which have potential for biological preservation The science in the landing ellipse is secondary the science outside the ellipse
Advantages: Space Architecture	There is a suitable landing or construction site on an eroded high plateau Construction material could be created from mining and processing phyllosilicates (sheet silicates) The area is relatively dust free	There is a relatively flat landing site at a lower elevation that its surrounding - decreasing radiation exposure There are surface clay minerals which can be used for ISRU purposes There is an increased solar energy gain and less complex dust control	There is a suitable landing zone next to an ancient channel valley There are surface clay minerals which can be used for ISRU purposes Due to the northern location, there are lower energy requirements	There are clay minerals and oxygen-bearing minerals which can be used for ISRU purposes There is a suitable landing zone which has been explored previously by the Curiosity rover The mean ground temperature is relatively stable

(*continued*)

Table 11.1 (continued)

Potential Sites	Holden Crater	Eberswalde Crater	Mawrth Vallis	Gale Crater
Disadvantages: Space Architecture	There are variations in the mean ground temperature There are long and intense winters, due to the southern latitude There are higher energy requirements and need for increased thermal protection	Exploration challenges may result from steep slopes There are higher energy requirements and the need for increased thermal protections	Challenges for surface operations may result from the boundary between southern and northern hemispheres	Exploration challenges may result from the high ridge of the crater The settlement's growth may be limited by the narrow flat area Dust control may pose challenges

Source: Elli Sol Strich, adapted from Häuplik-Meusburger and Bannova (2016).

Figure 11.5: A southerly view of Gale Crater, with the landing site indicated by the yellow oval (source: NASA/JPL-Caltech/ASU/UA).

2015); high levels of manganese, suggestive of a habitable aquatic environment (Lanza, et al. 2014); and basaltic lava indicating ancient volcanic activity (Gasparri, et al. 2020).

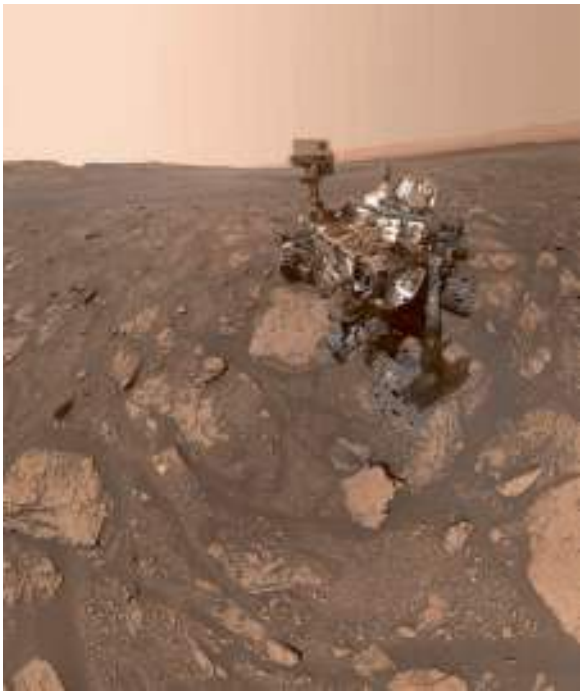

Figure 11.6: NASA's Curiosity Mars at "Mary Anning" in Gale Crater, October 5, 2020 (source: NASA/JPL-Caltech/MSSS).

Curiosity's work has in many ways weakened the argument for Gale as a landing site, due to the possibility of living or past living microbes being present in the region, and NASA concerns for planetary preservation (NASA 2021). NASA worries that human exploration and eventual settlement at Gale might disturb the ancient record of life on Mars. Ironically, the more Curiosity finds out about potential signs of life or water at Gale, the less attractive it is as a landing and settlement site.

The European Space Agency's ExoMars program is considering other landing sites where there may be signs of water activity or mineral deposits, like Mawrth Vallis, Oxia Planum, and Aram Dorsum (ESA 2021, n.d.-a, n.d.-b, 2021; Ivanov 2020). NASA's newest rover, Perseverance, considered Eberswalde Delta and Holden Crater, but instead landed on Jezero Crater in 2021. All three sites have been deemed promising locations for past water evidence or traces of microbial life (Smith 2020), but due to planetary preservation considerations determined by NASA, they are not ideal as a landing location for a future settlement.

The precedents described in Chapter 9 present a range of other considerations regarding siting, including the geographical benefits of the polar

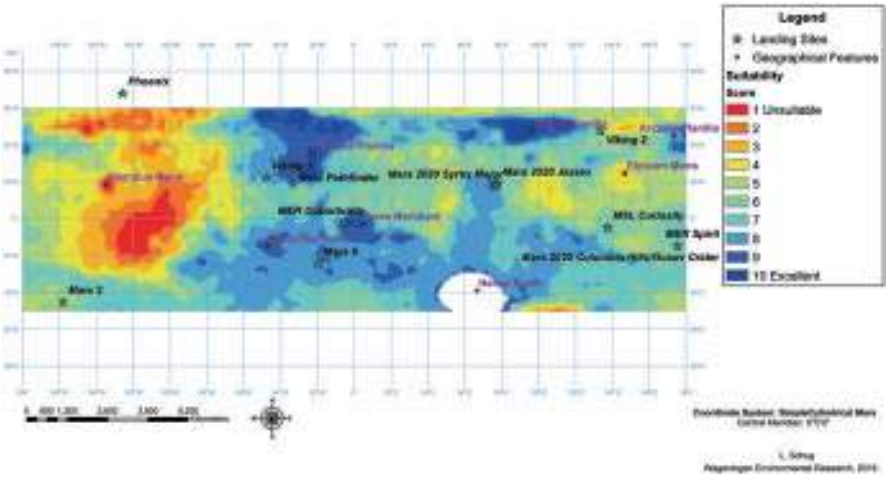

Figure 11.7: Suitability for plant life on Mars (source: Wagening University & Research; authors: Line Camilla Schug and Dr. ir. G.W.W. Wamelink 2018).

regions in contrast to the equatorial regions. Noted agrobiologist Dr. ir. G.W.W. Wamelink and his student, Line Camilla Schug, conducted a planet-wide suitability analysis regarding where on Mars plants would be most likely to grow and identified Utopia Planitia as one of the larger, more attractive locales (see Figure 11.7) (Glowatz 2018). One NASA contractor report that looked at transportation on Mars, cited in Chapter 5, made its own case for Utopia Planitia (30°N, 240°W) as an attractive location for a permanent settlement (Figures 11.8 and 11.9).

> Its favorable proximity to possible mining locations will facilitate the transport of raw materials to the base. Also, this latitude aids the ascent/descent vehicles by minimizing the plane change required to reach the orbiting transportation node which is at an inclination of 25°. Furthermore, this region is the largest flat area on Mars, which makes spacecraft landings, long distance travel, and communications easier. Finally, radiation shielding provided by the Martian atmosphere is increased (Ayers et al. 1992).

For this plan, I have followed suit and selected Utopia Planitia as a location for Aleph City. With its extremely flat topography, location proximate to the North Pole, and suitability for plant growth, Utopia Planitia has many attractive elements for hosting the first Martian city.

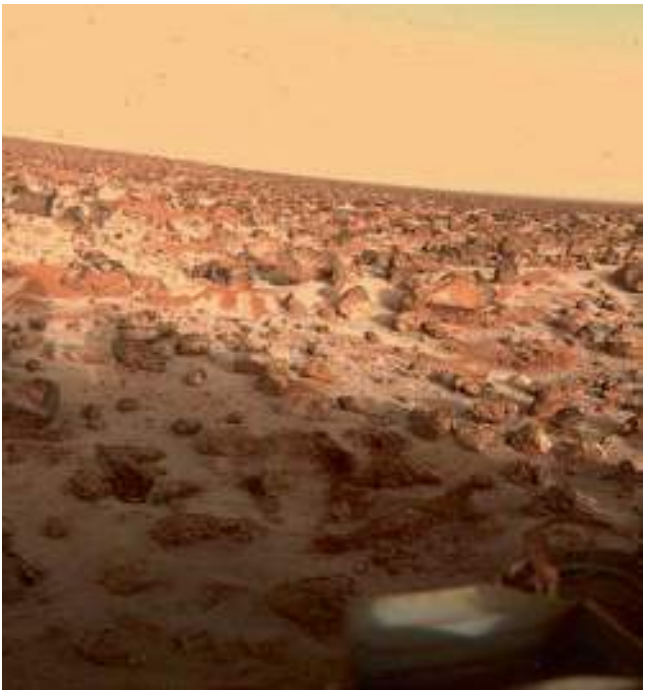

Figure 11.8: View of Utopia Planitia from the Viking Lander 2, 1979 (source: NASA/JPL).

Presentation of Design Concept

Overall Scheme

The first city on Mars will be largely underground. Like Kim Stanley Robinson's subterranean "moholes" in the early decades of his trilogy of Mars colonization, staying below grade (below ground level) protects people, animals, and plants from harmful radiation. Robinson modeled his moholes on NASA's Project Mohole, a 1960s proposal to develop vast underground tunnels to explore the region between the Earth's crust and mantle (The National Academy of Sciences 2021). Staying underground also helps modulate the wide temperature variation experienced aboveground.

Like Kozicki's (2008) Crater City concept described in Chapter 9, Aleph city is comprised of nodes of linked underground structures covered by domes. Kozicki, John Spencer, and others have written about the benefits of building at the sites of existing craters. In this plan, such extant depressions would be sought out, but if nothing suitable was found, sites could be excavated either mechanically or through explosives.

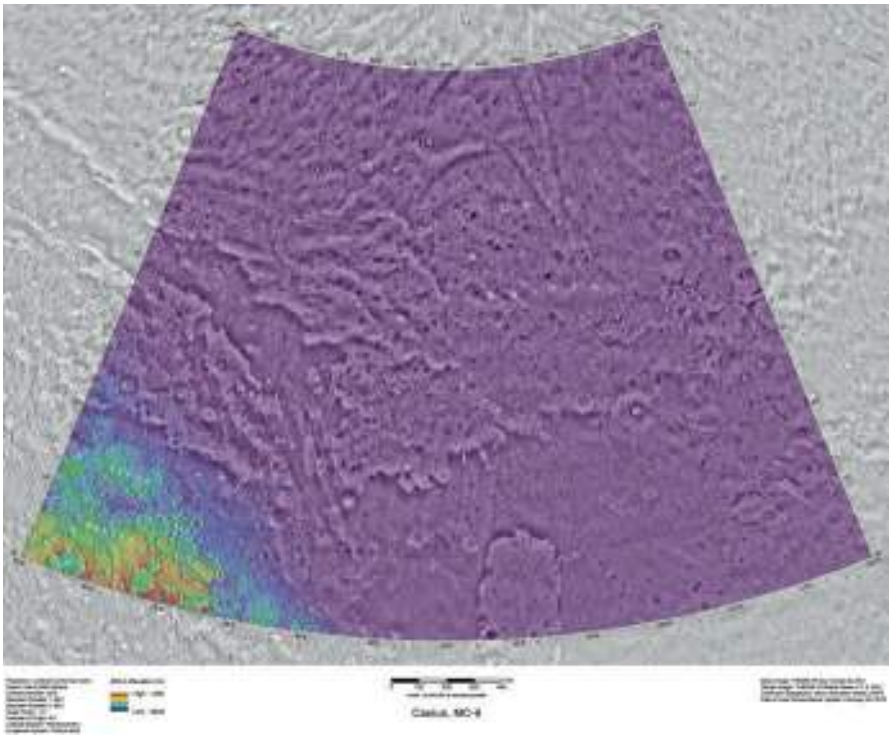

Figure 11.9: Topographic map of the Casius region of Mars, which includes Utopia Planitia (source: USGS, THEMIS imagery, www.usgs.gov/centers/astrogeology-science-center).

The basic building block of the settlement is a cluster of three sunken structures for living and working, each roughly 100 meters across and covered by a dome (see Figure 11.10). The size was selected purposefully, to use the intimate and familiar distance that people innately seek, as described in Chapter 2.[3]

The cluster is oriented in a triangular pattern and surrounds a smaller domed structure that serves as a communication and life support hub for the node. Each node is then connected via surface and subsurface transportation systems to the other two nodes and critical food, air, water, and related infrastructure systems. Further connections can be made to more remotely situated mining operations, nuclear power generation facilities, launch and landing sites for interplanetary travel, and an observatory (see Figure 11.10). Additional links can eventually connect to other settlements.

Each cluster of three structures is interdependent with the other clusters, as they all share access to infrastructure and storage facilities (see Figure 11.11). This design ensures a high level of redundancy, creates human-scaled

[3] Such a size also makes the construction of a dome less challenging than a larger sized structure.

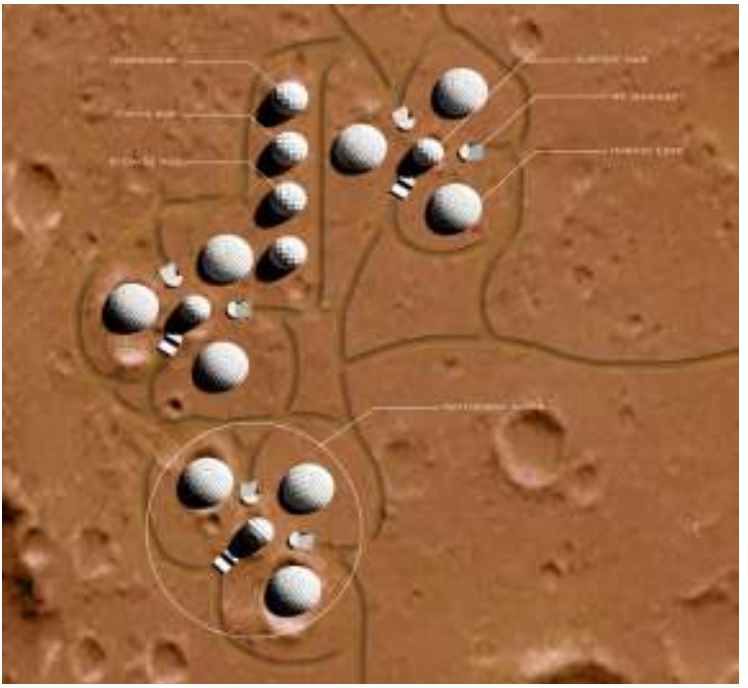

Figure 11.10: Plan view of Aleph City with three linked sets of nodes – each comprised of three habitat cores, tree rover garages, and a support hub in the center – along with greenhouse, mining, and storage hubs (infrastructure domes). Surface level rover paths are indicated in grey (source: Berk Diker).

environments and communities, and provides a variety of linked facilities and amenities. In the event of a catastrophic air pressure problem in one structure, people could easily relocate to a nearby one, kind of like having a second bathroom when the toilet clogs. It also keeps vital life support functions close by and hazardous uses far away but accessible.

Land Use Elements and Forms

The plan for Aleph provides for a range of land uses and organization of those uses into several integrated settings (Figure 11.11). The basic unit of the sunken structure is intended to be the primary location for human presence (see Figure 11.12). It is within these structures that most people will live, work, and play – the place where they will learn, study, labor, recreate, and have fun. Each is designed to go belowground three levels, with the lowest serving as the traditional Main Street for retail, dining, and access to underground train and bicycle/pedestrian transportation tunnels (Figure 11.13). The second level features institutional uses, including government offices, schools, health care

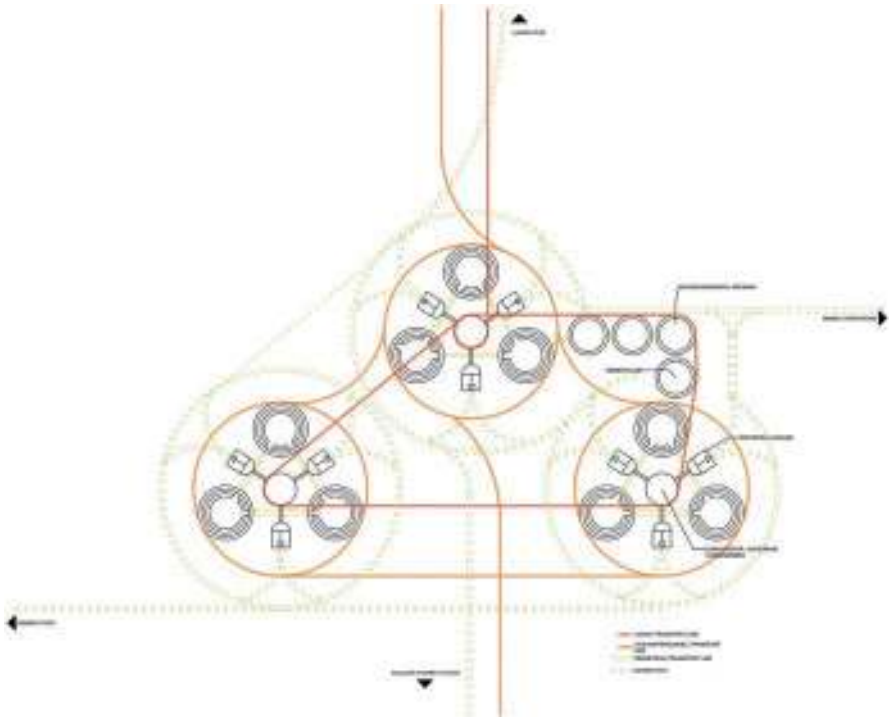

Figure 11.11: Plan view of cargo and passenger underground transit systems (source: Berk Diker).

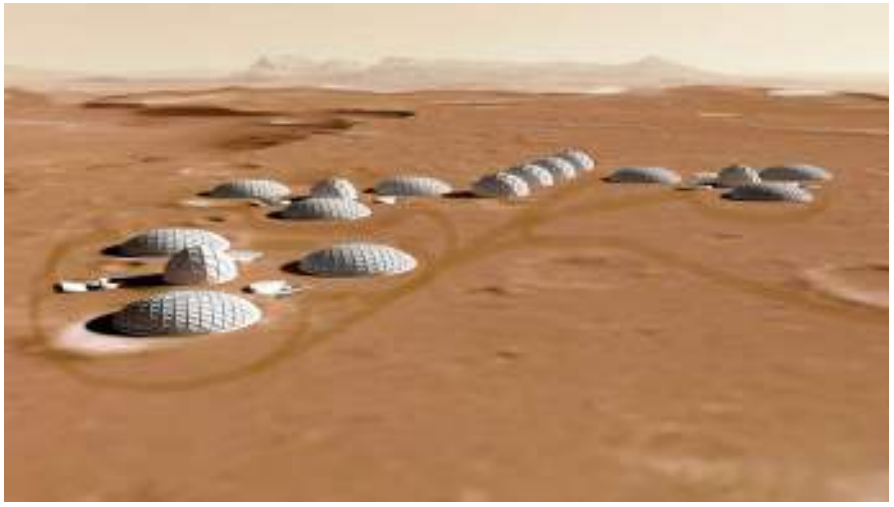

Figure 11.12: Exterior rendering of Aleph City, where domes cover three linked sets of nodes (source: Berk Diker).

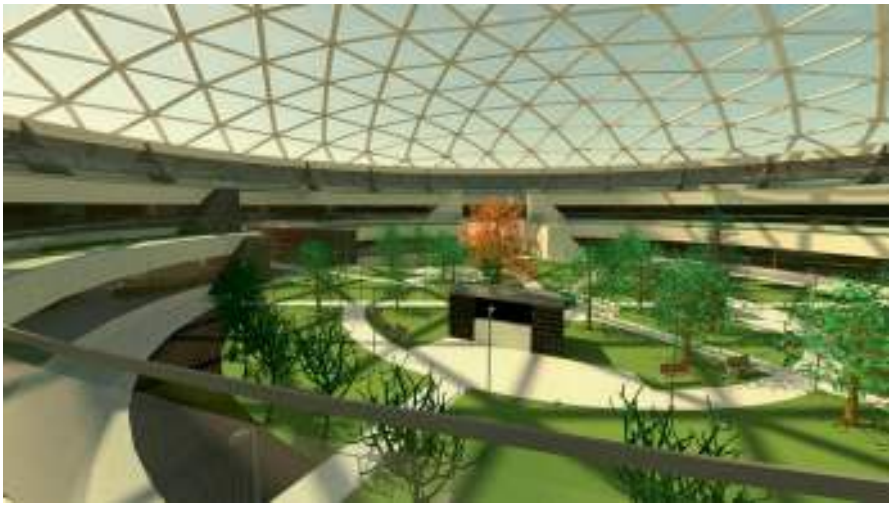

Figure 11.13: Rendering of the interior of the node (source: Berk Diker).

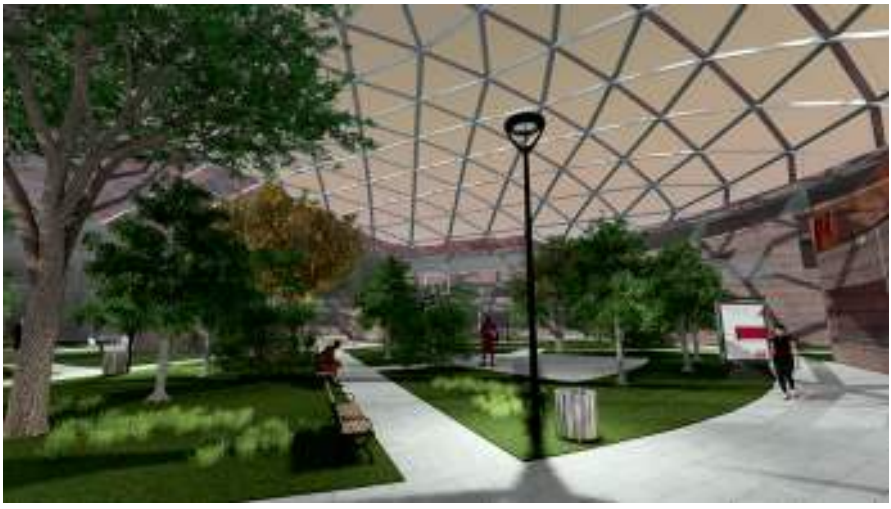

Figure 11.14: Rendering of the central park area of the node (source: Berk Diker).

facilities, and offices for mining, tourism, or other business. The third level is reserved for residential uses, including apartments, dormitories, and other living quarters (see Figures 11.14 and 11.15). The central courtyard of each structure would include green and recreational uses (see Figures 11.16 and 11.17), with some variation from one structure to another (more details on this in a later section of the chapter).

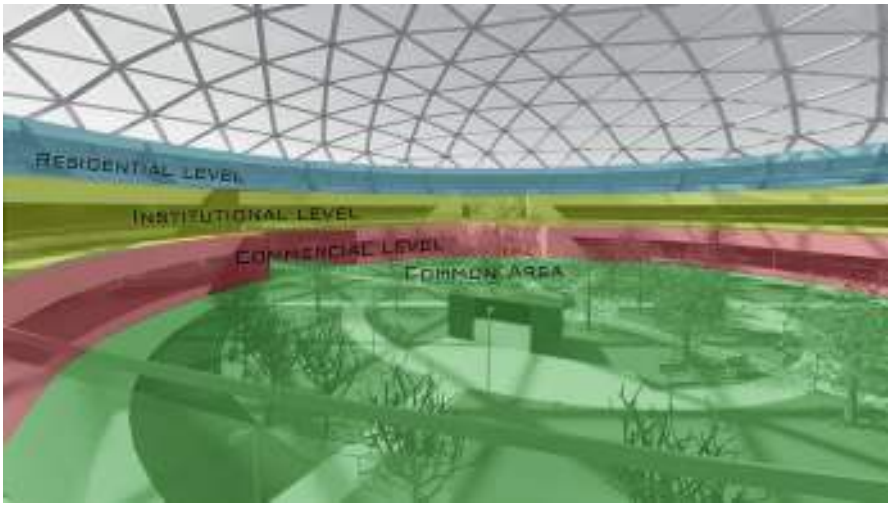

Figure 11.15: Colorized rendering to emphasize the vertical mixing of uses, from the perspective of the Institutional level (source: Berk Diker).

Figure 11.16: Section of a node illustrating the vertical mix of uses, from commercial on the ground floor, to institutional on the second level, to residential spaces on the third (source: Berk Diker).

Transportation

The transportation network for Aleph city provides a multi-modal and redundant system, allowing people to use human-powered transportation options (like biking and walking), shared fixed-route mobility (underground trains), and flexible aboveground rovers. There are two train systems, one for cargo (red line indicated in Figure 11.18) and one for human transport (orange line indicated in Figure 11.18). The human transport line connects the three structures to each other, to the other nodes, and beyond. The cargo line connects the central support hub structure for each node to the other support hub structures and to infrastructure facilities within the city and beyond.

Each central support hub structure includes three aboveground rover entrances, providing access to rovers for each node. The rover routes are

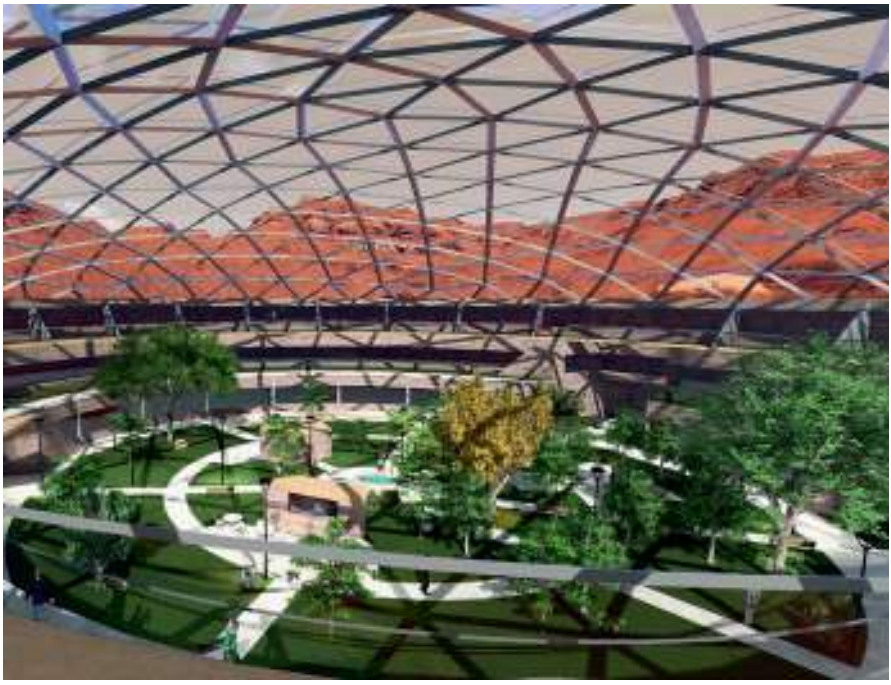

Figure 11.17: Interior rendering of a node (source: Berk Diker).

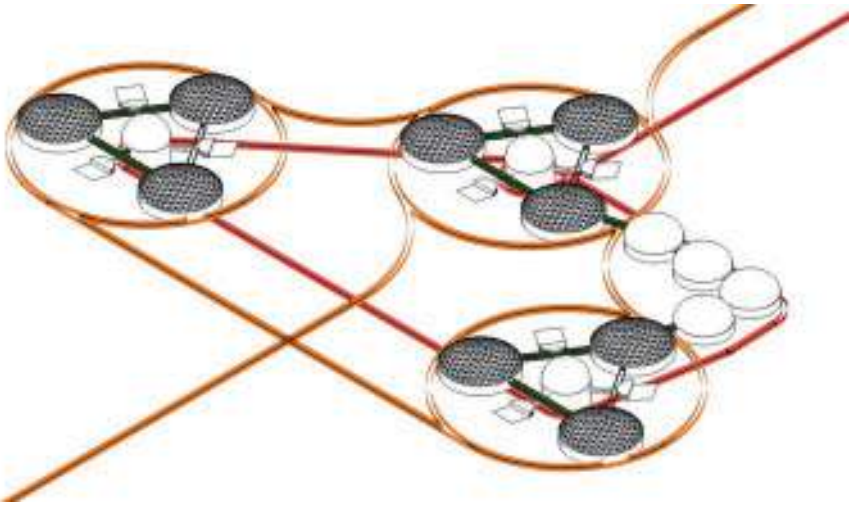

Figure 11.18: Rendering of the underground cargo rail system that links three nodes of Aleph City and beyond (source: Berk Diker).

indicated as a green line in Figure 11.19 and extend throughout the settlement, connecting the hubs to infrastructure facilities and all other areas of the city and beyond. Rovers are believed to offer the greatest flexibility for Martian exploration. Due to the low costs of building and maintaining roads for

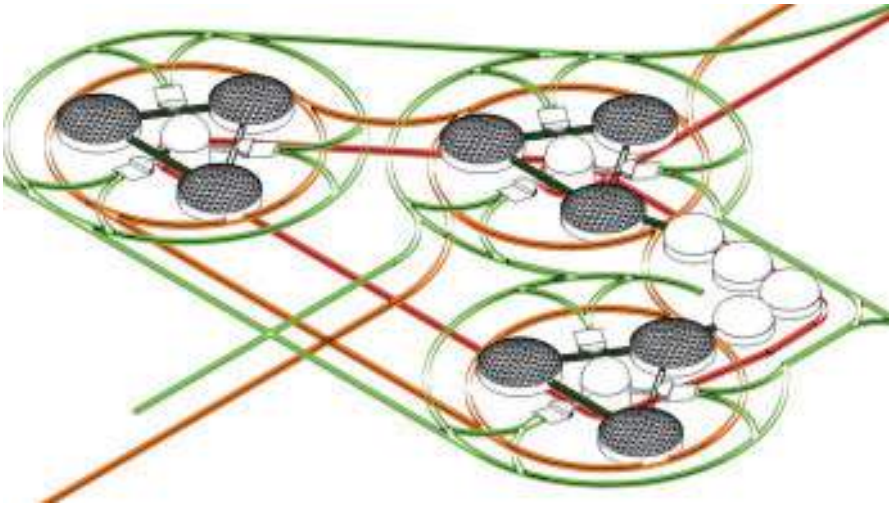

Figure 11.19: Rendering of how both cargo (red) and passenger (green) rail systems link three nodes (source: Berk Diker).

rovers, they can be an important element in the development of new settlements, connecting people and cargo before underground infrastructure is fully operational. Airborne transport is imagined here to play a minor role in connecting settlements, but could be used for exploration to distant parts of the planet.

Recreation and Open Space

The design of Aleph ensures that there are ample opportunities for walking and biking, but other recreation needs are anticipated given the difficulties of being outdoors on Mars. In addition, the benefits of access to open space and greenery are well understood (see details in the biophilia section of Chapter 4). As such, this plan provides a variety of open space and recreational opportunities. In the central courtyards of each of the three structures per node, a slightly different arrangement of active and passive outdoor-style activities is envisioned (see Figures 11.20 and 11.21). While some such spaces might be largely grass, benches, and trees, others might feature basketball courts, fountains, or community gardens. These courtyards are the primary place where Aleph inhabitants will receive solar exposure, which, given the dangers of radiation, needs to be limited. But those limits do not mean residents need to hide from the Sun, as sunlight can confer numerous psychological and physical benefits, and spending time in the courtyard can closely simulate time a person might spend outdoors on Earth. At nighttime, these courtyards can be

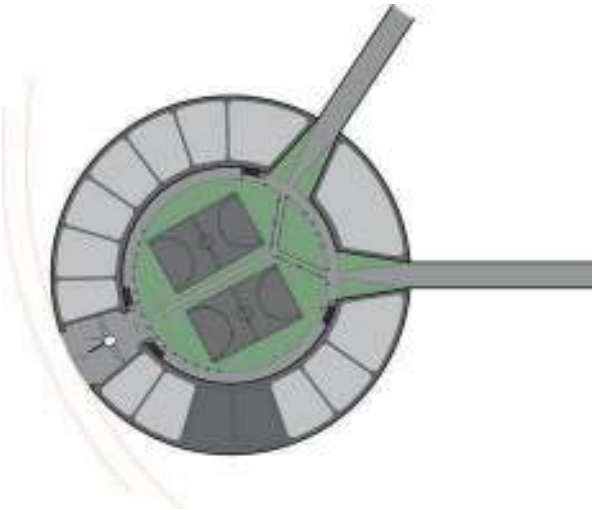

Figure 11.20: Plan view of a node settlement with formal ball fields, surrounded by institutional, commercial, and residential uses. Connections to other nodes are possible through rail and pedestrian links (source: Berk Diker).

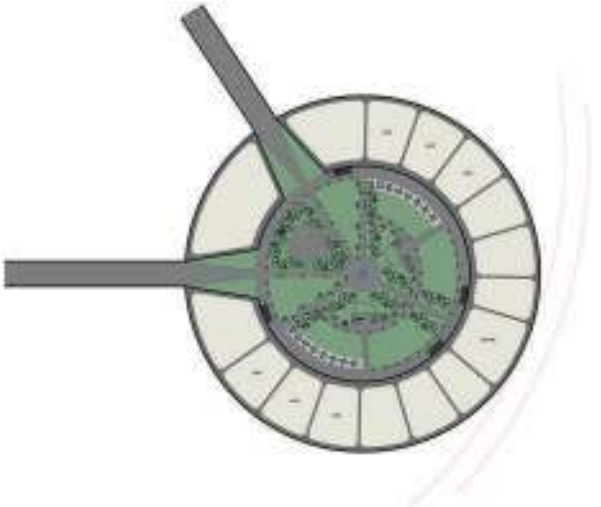

Figure 11.21: Plan view of a node settlement, with a central park and growing zones, surrounded by a range of commercial, institutional, and residential uses (source: Berk Diker).

spectacular places for community gatherings, for romantic strolls, or just for stargazing (see Figure 11.22). Without worries around daytime radiation, time spent in the courtyards past dark can provide Aleph residents with a place to relax and socialize in a physical environment reminiscent of Earth.

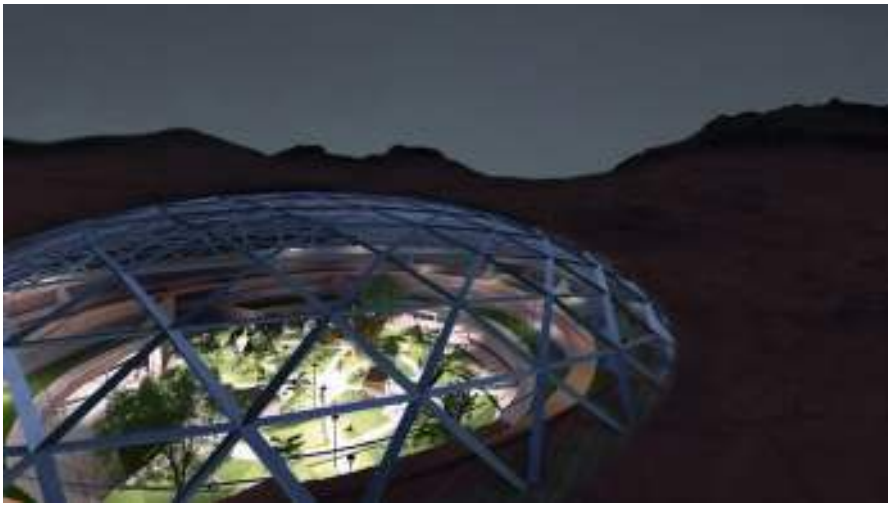

Figure 11.22: Nighttime rendering of a central park node in Aleph City (source: Berk Diker).

This will certainly be what our minds and our bodies seek (as discussed in Chapter 4).

Infrastructure

The basic functions to allow humans to live on Mars are all incorporated into this plan for the City of Aleph. Tanks for air and water are maintained in the support hubs at the center of each node. Additional air and water processing facilities are located just beyond the nodes in a cluster of four structures (infrastructure domes), accessible by both underground and aboveground transportation networks (see Figures 11.10 and 11.11). Those infrastructure domes also have room for storage, communication, and electrical needs.

The primary means of power is expected to be a nuclear power plant, located in a remote location far from Aleph. Eventual decommissioning of the nuclear plant requires proactive planning to anticipate a location closed off for human access for a long time. Given the need for energy redundancy, additional backup power sources are also needed. In Chapter 8, both solar and methanol were mentioned as particularly attractive. The infrastructure domes would therefore house the equipment, tanks, or related materials to support these kinds of alternative sources of electricity.

The infrastructure domes would also host food production activities, including greenhouses and livestock farms as appropriate. Food could also be processed and stored at this location and then transported to the live/work areas for consumption. In this plan, food preparation would be decentralized, with each housing unit envisioned to have its own cooking equipment, in addition to some shared cafeterias and other communal dining arrangements. Space in each structure's courtyards could also be available for gardens and even some animals like chickens or goats.

While not explicitly illustrated in these visual plans, waste would be managed with great care and attention. For human waste, the infrastructure domes would again be an ideal collection and processing location for recycling purposes. An underground network of pipes would be integrated into the transportation tunneling system displayed in Figure 11.11, facilitating the movement of a sanitary sewer system throughout the city. Food and other household wastes would also move from individual residential, institutional, or commercial spaces into the support hubs and then via an underground cargo train route to a centralized recycling and disposal facility within the infrastructure domes. Trash not recycled could then be transferred off-site to remote landfills in and around the mining operations or nuclear power station areas.

Mining operations, a nuclear power station, an observatory, and a launch/landing site extend from the city in the cardinal north, south, east, and west directions in Figure 11.10. Note that this is simply a schematic design, and the actual siting of each facility would need to respond to numerous scientific and engineering considerations. This plan simply communicates the requirement that such uses be located some distance away from the city and from one another.

Scalability and Regional Planning

The plan presented here for the City of Aleph is not a single city plan, but rather a blueprint for broader colonization of Mars. The basic conceptual design described above is well-suited for scalability and offers the requisite design vocabulary for a broader regional plan. The underground structures, nodes, and cities presented here can be replicated again and again to create a network of settlements, each with a unique configuration of courtyard, institutional, and commercial uses, but all maintaining the key infrastructure and land use needs to maintain human survival. A broader birds-eye view of Aleph demonstrates the larger context of the Martian landscape, with deep craters

Figure 11.23: Rover path system in and around Aleph City (source: Berk Diker).

and rocky terrain for kilometers (see Figure 11.23). Like Figures 11.10, 11.23 shows the arrangement of the three nodes and the abutting four infrastructure domes. While they are all connected underground, the aboveground rover path network is shown here. Each rover path terminates roughly 2 kilometers from the city, but that is only intended to demonstrate the large distances at which some remote facilities would need to be sited (e.g. the nuclear power plant).

Extending the logic of Aleph beyond its boundaries, Figure 11.24 shows what a rich network of a dozen such cities all in close proximity could look like.

Responding to the natural topography of Mars, the arrangement of each node, the placement of the four infrastructure domes, and the routes of rover paths are no longer so exact and straight. Figure 11.24 is an honest attempt to show how cities like Aleph can be expanded using the same design vocabulary and attention to safety and systems. As with City of Aleph, the regional plan for this broader urban expanse – Metropolitan Aleph – could employ a simple extension of the passenger and cargo underground rail lines originating at Aleph (see Figures 11.25 and 11.26).

In Figure 11.26, the extent of the view still does not include the mining operations, a nuclear power station, an observatory, and a launch/landing site, as they are still too far to see. Note that the rover paths also extend beyond the

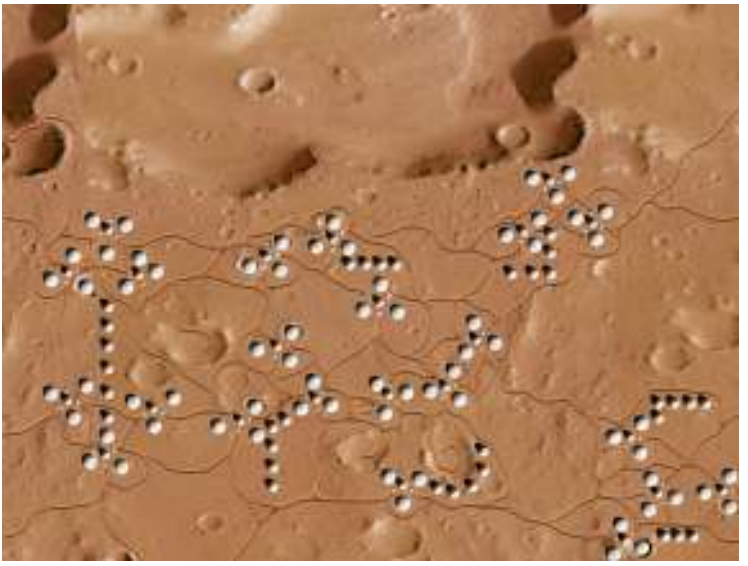

Figure 11.24: A regional view of the rover path network, extending far past the original Aleph City settlement (source: Berk Diker).

Figure 11.25: A regional view of underground cargo rail lines, with extensions far beyond the Aleph City settlement site (source: Berk Diker).

edges of the image. Like the rover paths, the underground trains would pass far beyond this view and connect with the mining operations, power stations, observatories, and spaceports extending far to the north, south, east, and west.

Figure 11.26: A regional view of underground public transit routes, with passenger lines extending beyond the original Aleph City settlement (source: Berk Diker).

Fictional Account of Life in Aleph

This Plan for Aleph, the first city on Mars, offers a sound template for colonizing the Red Planet. The plan builds from the many precedents presented in Chapters 9 and 10. It addresses the key considerations any planner on Earth would face in regards to housing, transportation, waste, etc., while also weighing the difficulties of drastically lower air pressure, poisonous radiation, and poisonous air, among other difficulties. The result is a textual and visual expression of the principles introduced throughout this book.

Before moving on to the concluding chapter of the book, indulge me by following this tale of what living in Aleph might feel like – what it might mean to have a life in this distant land.

Still weary from the long spaceship ride from Earth, Jae slumps in his seat as the underground train rides almost silently on its half-hour journey to Aleph. Pulling into the first station, a digital announcer notifies all passengers that they have arrived at node 1. Jae waits patiently as the train proceeds to node 2, and then at node 3, he disembarks. The underground station is busy, but not hectic. The room is well lit, the air just a bit off from what he's been breathing on his trip from Earth, and the air pressure change isn't noticeable at all. Signs point to the sunken structure he was told to first report to: Structure B. A network of tunnels is full of people walking and separate pathways for bicyclists; Jae maneuvers the scene with ease.

Within five minutes, he climbs a set of stairs, skipping the elevator, and approaches Level 1, full of a range of commercial uses, including the train station office, cafes, shops, and a bookstore. His stomach rumbling, he pops into a convenience store and buys a banana – something he didn't realize they grew on Mars.

Emerging from the store, Jae is stuck by the beauty of the courtyard, a vast green space with trees, grass, and a plaza where children are riding bikes and parents are spectating. Looking up, he sees the Martian daytime sky, the distant Sun, and the shimmer of reddish-brown craters across the landscape. Jae strolls along the circular path of the first floor level and then climbs the stairs to Level 2. Signage tells him that this level is occupied by a dentist, physical therapist, offices for the nuclear power company, and his destination: the architecture firm that just hired him.

Looking back at the courtyard and beyond, the view is even more impressive. Higher up now, he can see more of the blood-red terrain, and looking down at the courtyard, he better appreciates the Earth-like scene before him. So many months and so much distance from home, he feels a deep warmth in his abdomen at the sight of grass, shrubbery, and trees.

After meeting with his new supervisor and introducing himself to some colleagues, Jae heads to his new apartment to catch up on some sleep – he would start at work the next day.

Up one more flight of stairs, again eschewing the elevator, Jae arrives at the residential level of Structure B. Now just a mere few meters from the surface, he finally gets a commanding view of the Martian landscape, and it is spectacular. The rocky reddish-brown land stretches for kilometers before him, pocked by dozens of craters and accented by the occasional small hill. Utopia Planitia astounds him with its flatness, allowing him to gaze far into the distance – what feels likes a million kilometers into a vast and empty land.

The residential floor does not feature the same bright and eye-catching signage as the lower two floors. Here, residences are labeled more discreetly. After some navigating, Jae finds his assigned apartment and uses the key card his employer gave him to open the door. Inside, a full 500 square feet of living space appears before him, fully furnished with a bed, dresser, couch, desk, and a kitchen replete with cooking appliances. He looks up and through skylights sees the dome roof and Martian sky beyond. He was warned to keep the skylights closed during most daylight time he is in his apartment, so Jae takes one last gaze above and then shuts the skylights, turning the electric lights on instead.

Exhausted from his travels, Jae falls into his freshly made bed. A new bed, a new home, a new city, a new planet. Aleph was going to be the adventure of a lifetime!

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12

Conclusion

Considering the astronomical costs to get to Mars, the immense engineering obstacles, the radiation, atmospheric pressure, poisonous air, and lack of water, it would seem impossible to even imagine ever landing a human crew there. The myriad challenges strip away at the feasibility of a long-term, substantial human settlement on the Red Planet. But here we are, planning anyway.

Sitting on my back porch with my family one recent summer evening, my teen-age daughter jumped up and exclaimed, "Dad, there's Mars!"

For millennia, humans have been able to see that small reddish dot in the night sky. The dream, however impractical, of building a new home for humans on Mars cannot be so easily dashed. As long as dreamers have money and some modicum of technical expertise, they will continue to reach for the Red Planet. As they do, let us be ready, thoughtful, and prepared for what just might make us a multi-planetary species.

Limitations and Suggestions for Future Research

As with any scholarly endeavor, there are important holes and weaknesses in this book that are important to review here. As with any historical treatment, decisions must be made regarding where to start and stop and how much depth to go into. My treatment of Earth's own colonization experiences was concise and omitted vast territories and epochs of settlement. What I presented in Chapter 2 were only illustrative of the kinds of experiences humans have had. In the same way, my grappling with the horrors of colonization was

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limited. Others should do more to engage with this record more directly and attempt to conceptualize the colonization project in such a way that Martian settlement does not repeat that history, through planetary degradation or other pathways.

In Chapter 3, my review of space exploration and architecture and planning experiences, both on Mars and elsewhere, is more concise than some readers might like. In an effort to provide just enough context for the remainder of the book to make sense, I had to summarize key events and trends.

The presentation of key concepts from psychology and neuroscience in Chapter 4 offer important principles for planning a city on Mars, but these are only a selection of the kinds of principles one might find in a review of this literature. This is a growing and complex field of inquiry, and new discoveries are regularly appearing online and in print, meaning that our understanding of the human mind and body is constantly in flux. Today, this material is accurate, but much remains unknown until humans set foot on Mars and field experiments can be conducted to validate the principles presented here. Similarly, Chapters 5, 6, 7, and 8 rely on scientific data, experiments, and experiences that are subject to updating. All the principles introduced throughout the book are presented in the sincerest spirit, but must always be read as highly subjective, contestable, modifiable, and in need of reconsideration as new evidence emerges.

The precedents reviewed in Chapters 9 and 10 covered a range of examples, yet they are by no means an encyclopedic collection of all ideas ever generated about building cities off-Earth. Chapter 10's plan for Aleph City was just one of millions of possible configurations of land, buildings, and infrastructure. In collaboration with my design partner, Berk Diker, the plan presented is what we consider to be the best such configuration, but that is just our opinion.

Others might approach the planning process quite differently. For instance, the Lincoln Institute of Land Policy and other scholars have been studying "scenario planning" as a tool for projecting how a range of possible futures can be adequately planned for (Holway et al. 2012; Chakraborty et al. 2011). Through computer simulations of land use and development scenarios, planners can work with communities to make informed decisions about the plan they might want to adopt. For Aleph City, scenario planning offers a framework to consider how a range of climactic, transportation, or resource issues might be integrated in a final plan for development.

Rather than attempting to translate the principles from earlier in the book into a plan, another exciting alternative would have been to draw on the engineering field of operations research, converting those principles into a mathematical equation that would dictate the dimensions and qualities of the plan for Aleph (Johnson 2011). I have tinkered myself with this approach in my own research and recognize the value of converting purely subjective principles into objective outcome variables, thereby illuminating our planning choices, whether here on Earth or a distant planet (Johnson et al. 2021).

For many years, Google (aka Alphabet) owned an urban planning firm, Sidewalk Labs, which in 2020 launched a tool to support real estate development and planning: Delve. Google calls Delve a 3D generative design tool. It draws on numerous data sources and runs machine learning models to propose a range of land development configurations, similar to what previous tools could do in maps, text, and tables (Johnson et al. 2021). Delve or similar tools could be employed in future research to extend the Plan for Aleph City into 1,000 plus plans, where each could be tested and studied before implementation. This Delve approach could even be used in concert with the scenario planning or operations research approaches. With the aim of optimizing key goals while working within the constraints of a challenging environment, advanced data science and engineering can offer useful improvements on the design process and offer a broader range of testable solutions to planning a city on Mars.

Key Findings

In this book, I have sought to offer an expansive treatment of the settlement of Mars by first reviewing some of the history of human colonization of regions of Earth (Chapter 2), reviewing space architecture and planning writ large (Chapter 3), giving some perspective on the psychological dimensions that ought to be considered (Chapter 4), and then cataloging the science and engineering dimensions of residential, commercial, industrial, and infrastructure development that would be relevant in a Mars city design (Chapters 5, 6, 7 and 8). With that knowledge as a foundation, I reflected a bit on precedents for planning beyond Earth (Chapters 9 and 10), generating the examples needed to develop a plan for a new city on Mars (Chapter 11).

All this constitutes the work that an urban planner might do for any geography on Earth: a summary of history, analysis of conditions, collection of precedents, and articulation of a vision through a detailed written and rendered plan.

It is worth noting that I am not a utopian. The allure of a new planet as a place to start fresh and build a more perfect world than on Earth is a widely expressed sentiment (Krieger 2019; Fishman 1977; Friedmann 2000; Solinís 2006). I am less sanguine on such a possibility and am swayed by Ray Bradbury's *Martian Chronicles*, which concludes with a dark message for humanity: you are doomed to repeat the flaws in your society that you created on Earth. Nevertheless, exploring, building, and expanding are traits humans have held throughout our history, and to suggest that people will not try to colonize Mars is obtuse. As such, my genuine hope is that when such colonization happens, this book will serve those intrepid pioneers by offering them the historical context of the colonization enterprise, the science and engineering know-how, and a well thought-out diagram for how to do their work.

As discussed, the science and engineering reported here will be dated as soon as this book goes to press. In future editions of the book, updates can be made, but the fast pace of progress means that others will need to do the work of reviewing the conclusions to ensure that the key principles derived from each chapter remain valid and sound.

Naysayers might conclude that the science and engineering challenges introduced in the previous chapters are insurmountable, and we have had to suspend some disbelief to see the broader picture. So, what if we never make it to Mars, never managing to sustain even a basic scientific observatory? In that case, the message of this book remains relevant in two ways.

First, even if Mars cannot be colonized, there may be other celestial bodies that can, and the research presented here can be adapted for those environments and climates. In Chapter 3, the moons of Jupiter, asteroids, and even our own Moon are presented as potentially viable future homes for humans. The imagined plans for settling these locales are painted vividly in Chapter 10, stirring the possibility that even if settling Mars never happens, building a city on Europa or the asteroid Vesta might be possible.

Second, there is much in this book that can help us right here on Earth. The frigid and foreboding environment of Mars resembles much of the

North and South Poles of Earth. Even thousands of miles from the Poles, the frozen deserts of Baffin Island in Canada or the vast field stations of Antarctica are largely devoid of human inhabitants today. But, as our own planet faces changes and disruption, these unwelcome places may find themselves newly attractive. Rather than approach them haphazardly, the findings of this book provide insight into settling these difficult landscapes as well.

Implications for Design Practice

While space architecture has been around for generations, and skilled designers have sketched out plans for structures on the Moon and Mars and given shape to the International Space Station, space urbanism remains in its infancy. It is an interdisciplinary idea, drawing on the sciences, engineering, psychology, political science, sociology, economics, and other disciplines. The outlines of this field are baked into the table of contents for this book. It has a grounding in the history of settlements, with particular focus on colonization; an understanding of the psychological and health needs of people as a first principle for approaching this kind of planning; an engagement with the substantive areas of residential, commercial, industrial, and infrastructure and how they function both on and off Earth; an understanding of the science, climate, topography, features, and history of other worldly places; and an understanding of the planning and design process that brings together insights from all of these other topics to bear on a physical design for large-scale human settlements. As with any new field, space urbanism will need established curriculum, formal training programs, and professional development infrastructure. There is time to develop all of this, and this book can serve as a baby step towards such activities. Professionals coming from all of these disciplines can join this new field, offering a variety of perspectives when planning off-Earth cities.

Final Thoughts

In 2020, Netflix launched a new television drama about Mars exploration called *Away*, featuring Academy-award winning actress Hillary Swank. Unlike the typical action adventure Mars story, this one is centered on

Swank's character, the commander of what is to be the first spaceship to bring people to Mars. Their mission is purely scientific and will only involve a short months-long stay, but it purports to be the first step in a wider settlement of Mars. The trip is viewed by Swank's character's family as perilous, and the tradeoffs between personal ambition and family are explored.

For the *Away* show, the engineering innovations involved in getting to Mars are a minor plotline. The show is about humankind's "voracious yearning for exploration" (p. 9). Like this book, the show puts people first, exploring questions about how we will experience Mars, how it will affect us, and how we can make Aleph City feel comfortable and welcoming – making our emotional and human selves central to the storyline.

The technology was likewise impressive but not the star of the show in 1969, when American astronauts first walked on the Moon. During the live broadcast of the landing, a British Broadcasting Company (BBC) anchor said, "This is a powerful reminder of our capacity for greatness as a species. Not simply the engineering triumph represented here today, but the triumph of human ambition, the desire to reach quite literally for the stars." That "triumph of human ambition" is what will bring people to Mars one day, and it is also what will make them stay, settle, and thrive.

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Glossary[1]

Additive Manufacturing Widely considered to be synonymous with *3D printing*. Uses digital directions in the form of a 3D computer-aided design (CAD) model to direct a machine to manufacture an object by layering materials over each other in order to generate three-dimensional shapes.

Aerial Tram A type of transportation lift using cable cars and rope systems.

American Planning Association A U.S.-based membership organization for urban and regional planners.

Antarctic Treaty of 1959 A treaty that laid out systems of conduct and outlined Antarctica's status as a neutral, collaborative land that isn't owned by any one national power.

Artemis Program NASA's current plan to revisit the Moon and settle Mars.

Bernal Sphere A spaceship designed to accommodate large quantities of people that provided inspiration for further designs.

Bilateral Symmetry The property of being divisible into two identical, mirrored halves.

Biophilia The inherent love humans have for nature and life.

Biophilic Design Incorporating an innate need for natural light, green spaces, and natural shapes and forms into architectural and urban design.

Built Environment All areas developed for human settlement and ancillary uses, including roads, buildings, and utilities. Considered an antonym of the natural environment.

Centering The erection of support systems that provide the form for an arch or vault before it can support itself.

[1] Prepared with assistance from Alyssa Eakman

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Cliff Dwellings A form of usually underground living that uses cave systems built into cliffs.

Closed Loop System A system that does not gain or lose materials, but instead perfectly recycles materials in the system.

Cognitive Architecture An approach to the planning and design of the built environment that is grounded in evolutionary biology and psychology, focusing on how people unconsciously experience buildings and places.

Dead Load A relatively constant weight, like structural elements and flooring, that weighs down a building and requires substantial foundations to hold it up.

Delve An Alphabet/Google-owned design tool that develops various 3D models of land configurations.

Ductility The ability of a material to be deformed from tensile strain without collapse.

Electrolysis A process that uses electricity to split water into oxygen and hydrogen gas.

Elevational Plan A form of underground settlement built into the sides of slopes.

Evapotranspiration Water evaporated from the surface of a planet into its atmosphere.

First Principle The requirement that basic human needs be met in the design of the built environment.

Façade The front (or side) of a building that directly faces a public street or plaza.

Forum Classical Roman name for urban plazas, where people gather for communal and social activities.

Galactic Cosmic Rays A form of constant low-dose radiation that are difficult to shield against.

Geodesic Dome A lattice-shell structure that uses triangular elements of geodesic polyhedrons to withstand heavy weight.

Golden Rectangle A specifically proportioned rectangle that is considered the most preferred shape due to certain naturally appealing ratios, approximately 1:1.618.

Grand Modell The city planning template designed by the British that uses square grids, standardized dimensions, and specific urban features.

Great Places a program of the American Planning Association that identifies exemplary public places.

Grid Pattern the layout of streets and roads along generally north-south and east-west axes, where all intersections meet at 90-degree angles.

Hexmars Design A settlement concept designed by Prairie View A&M University to house gradually larger numbers of astronauts.

Hierarchy The property of being organized into clearly identified top, middle, and bottom sections.

Homestead Layout A Mars settlement concept by the Mars Foundation that uses a linear layout.

Horizontal Mixed-Use Different uses are located in separate buildings in the same general area.

Hydroponics Growing plants in a mineral solution instead of traditional soil.

HVAC Stands for Heating, Ventilation, and Air Conditioning system.

Imageability A measure of how a space will evoke emotion and create a lasting mental image through patterns and proportions.

International Space Station (ISS) A large modular space station that currently supports astronauts and is used by scientists to conduct research in space.

Land Use The activities that people are engaged in on a given piece of land. The most common categories in urbanized areas include residential, commercial, industrial, institutional, transportation, and other infrastructure.

Law of the Indies A widely used set of standard rules for urban planning written by the Spanish in the 16th century.

Low-Earth Orbit A region of orbit usually at an altitude of less than 2,000 kilometers above the Earth's surface.

Magic Square A specific square pattern originating from Chinese culture that influenced the early layout of Asian cities.

Mars Direct Plan A comprehensive plan to colonize Mars developed by Dr. Robert Zubrin.

Mars Exploration Program Analysis Group (MEPAG) A group of scientists who organized with the aim of creating a plan to guide Mars missions.

Master Plan A comprehensive examination of the spatial, social, economic, environmental, transportation, and other characteristics of a geographic area – typically a city or town – with the aim of devising goals and the means to achieve those goals for a medium- to long-term time horizon.

Micro-Ecological Life Support System Alternative (MELiSSA) A project aimed at designing greenhouse and agricultural developments for permanent Mars settlements.

Mixed-Use Development Buildings that feature more than a single use, for example commercial businesses on the ground floor and apartments on upper levels.

O'Neill Cylinder A cylindric spaceship concept adapted from the Bernal Sphere.

Open Space Undeveloped land dedicated to a range of either active or passive recreation or natural conservation purposes; includes parks, nature preserves, gardens, and sports fields.

Penal Colony A colony designed to house prisoners exiled from the rest of society.

Public Realm Those outdoor spaces between buildings and streets where people are free to gather, socialize, and recreate – notable examples include parks, plazas, sidewalks, and trails.

Regolith The loose rocks and soils found on the surface of both the Moon and Mars.

Rolling Resistance How much resistance a travelling vehicle's wheels will face as they traverse the lunar surface. Measured as a coefficient, where 0.01 represents the weight of 0.01 pounds needed to pull one pound of weight.

Sintering The process of heating solid materials to a liquid form; used in manufacturing a new material, including construction bricks or blocks.

Site Plan A detailed physical plan for a site, depicting the location of existing and proposed roads, paths, transit, open space, and the footprints of buildings.

Smectite A type of clay found on Mars that may sustain plant life.

Stanford Torus A space station design using a doughnut or toroidal shape.

Streetscape The combined elements of roadways, sidewalks, street furniture, vegetation, plazas, and buildings that are visible to a pedestrian as they pass along a street.

Sunken Courtyard A form of underground building that creates an exposed center with protected living areas on the underground edges.

Thigmotaxis The idea that there are specific rules unconsciously influencing how animals and people orient themselves in a space, including a preference to maintain tactile connections to walls and edges. Also known as wall-hugging.

Topography The forms and features of land, particularly regarding elevations.

Urban Design An activity at the intersection of architecture and urban planning, focusing on the design of the built environment at the city or neighborhood scale – attending most closely to the public realm.

Urban Planning A place-based, future-oriented activity to guide community change, involving the setting of goals and means to achieve those goals, derived through some level of public involvement.

Vertical Mixed-Use Different uses are located on separate levels of the same building.

Vitruvius Roman philosopher and writer, author of one of the first books articulating a theory of good architectural design.

Watershed Planning Management of water resources at the regional scale comprising a watershed, where rainwater drains to a common body of water.

Zoning A local government policy tool that allows for the dividing up of cities into various distinct uses such as residential, commercial, and industrial areas.